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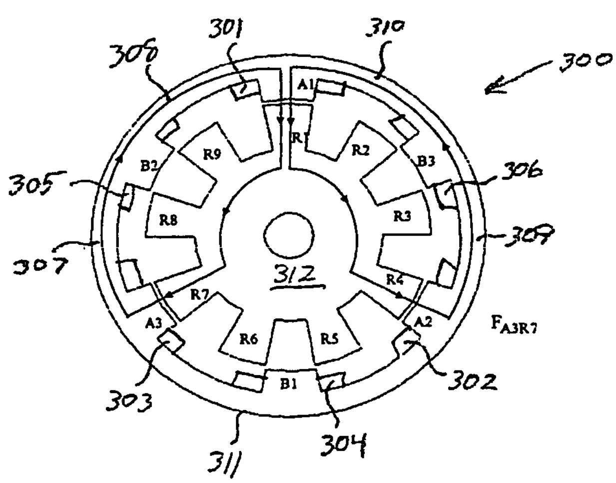
(54) Title: APPARATUS AND METHOD THAT PREVENT FLUX REVERSAL IN THE STATOR BACK MATERIAL OF A TWO-PHASE SRM (TPSRM)



(57) Abstract: A two-phase switched reluctance motor includes a stator (311) made of ferromagnetic material with stator poles and a rotor (312) made of ferromagnetic material with rotor poles. There are two-phase windings (301-306) on the stator poles. The number of stator and rotor poles are selected such that no flux reversal occurs in any part of the stator core as a result of transitioning between the first and second excitation phases.

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CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Application No. 60/454,630 and incorporates by reference this provisional application in its entirety into the present application (see Appendix A). Additionally, the application hereby incorporates by reference the disclosures provided in Applicant's co-pending PCT International Application Nos. PCT/US03/16627, PCT/US03/16628, PCT/US03/16629, PCT/US03/16630, and PCT/US03/16631.

BACKGROUND OF THE RELATED ART

There is an emerging interest in very high speed machines, having speeds in the range of 20,000 to 60,000 revolutions per minute (rpm), for use in appliances, aerospace, and other applications. The foremost features that are required for these machines are high efficiency and low acoustic noise. For high efficiency operation of these machines, it is important to examine the dominant effects of each and every loss in the machine. There are three dominant losses to be considered in these machines that impose significant design and operational constraints. These dominant losses are: (1) copper or resistive losses, (2) core losses, and (3) frictional and winding losses.

Copper or resistive losses result from the flow of current in the stator windings. The windings invariably have resistances, and currents in them produce a voltage drop, v,

equal to the current, i, times the resistance, R, expressed as $v= Ri$. Since a current is flowing through the resistive element, the voltage drop produces a power loss, p, across the windings equal to the current times the voltage drop, which, in turn, equals the resistance times the square of the current, which is expressed as $p = vi = i^2R$. For a given power, if the current is minimized, then the only parameter to impact the resistive power loss is its resistance.

The resistance for a given winding varies with its temperature and a skin effect. Temperature sensitivity is determined by a physical coefficient of the winding material and the temperature rise in the windings due to their excitation. The temperature rise can be controlled by a cooling arrangement, and its upper limit is determined by the thermal capability of the winding's insulator material. Therefore, there is not much that can be done to reduce the resistive losses beyond optimizing the winding material and its cooling arrangement.

The skin effect is due to the frequency of the current that is flowing in the winding and is controlled by the phase switching frequency (PSF), which is different from the pulse width modulation (PWM) frequency. The PSF is determined by how many times a phase experiences current per unit time (i.e., a second) and is determined by the number of poles of the switched reluctance machine (SRM). Therefore, the PSF can be minimized by minimizing the number of poles and operating

the machine at lower speed. While the pole numbers can be minimized, the upper speed limit is not determined by the machine but by the application, and, hence, the upper speed (i.e., the highest speed that the machine will experience) is a dominating factor in the machine design.

In the final analysis, it can be deduced that the resistive losses are determined by: (a) temperature sensitivity of the winding material and (b) frequency of the alternating current (ac) component of the current, primarily that of the phase switching frequency. The frequency of the current's ac component is determined by the number of poles of the rotor and stator and by the upper speed of the machine, which is determined by the application and not by anything one can do in the machine design. Therefore, the upper speed of the machine is an independent variable. The temperature sensitivity of the winding material, the frequency of the ac component, and the number of rotor and stator poles can, however, be controlled by the machine designer, within the constraints of the physical characteristics of materials and the necessary pole numbers. Therefore, the resistive losses can be minimized to an extent.

Besides resistive losses, core losses constitute another type of the dominant losses affecting TPSRM design. The core material of a TPSRM experiences a loss due to the varying flux flow in it. The core losses consist of two parts, hysteresis loss and eddy current loss. The hysteresis loss is influenced

by the frequency of the flux and flux density in the material and a physical factor of the material. The frequency of the flux is determined by the phase switching frequency, which in turn is determined by the upper speed of the machine. Assuming that flux density is kept at a desired level to generate the required torque, then the factor that is under the control of the designer is the phase switching frequency, but only to an extent as explained above.

Eddy current loss is due to the flow of eddy currents in the laminations and is a function of the square of the frequency and the square of the flux density, as well as other variables, such as the square of the thickness of the lamination material. The thickness of the lamination materials is determined primarily by the cost, and, hence, it is prefixed for each and every application. Therefore, to minimize the eddy current loss, the designer has to minimize the flux density and phase switching frequency.

From the above discussion, it may be seen that is important to reduce the frequency of the phase flux and the magnitude of flux density in the material, to minimize core losses.

The third type of dominant loss affecting TPSRM design is friction and winding loss. This type of loss is a function of the rotor and stator pole shapes and the air gap between them. Given an electromagnetic design of the stator and rotor pole shapes, there is not much that can be done to reduce the

friction and winding losses, other than filling the rotor interpolar space with a magnetically inert material, so that the rotor is cylindrical. Also, the stator may be constructed with a thermally-conducting, but magnetically inert, material between the coils of each pole and its adjacent pole, so the stator's inner surface is full of material with no gap other than the air gap in its vicinity. But this is a cost issue, and, therefore, it may not be possible for all applications, particularly for low-cost applications, such as in home appliances.

From the above discussion of the various machine losses, it may be discerned that it is important to minimize all the core loss components, but most importantly the ones that will dominate in the final analysis, related to electromagnetics in very high speed machines. These components can be minimized by controlling the flux density and also by minimizing the frequency of the flux in the materials. Once the pole numbers and upper speed are fixed, the frequency of the flux is also fixed. Thereafter, the design variables available to the designer for minimizing core losses are few or nonexistent. Examining very closely the core losses for various parts of the machine, such as the stator and rotor poles and the stator and rotor back irons, a degree of freedom in tackling the core losses becomes evident. That is, the designer can minimize the core losses in each and every part separately. The core losses for these parts are described below.

The stator and rotor back irons usually have bipolar flux in most SRM machines and experience flux reversals. In the stator poles, the flux density should be maximized for a minimum of material weight. Stator poles do not experience flux reversals. The flux in the rotor poles is also bipolar and designed not to exceed the maximum peak flux density of the materials.

Fig. 1 illustrates a related art TPSRM having 4 stator poles and 2 rotor poles (a 4/2 stator/rotor pole combination) and the machine's flux paths when phase A is excited. Fig. 2 illustrates the TPSRM of Fig. 1 and its flux paths when phase B is excited. Phase A consists of windings 101 and 102 on diametrically opposite stator poles 105 and 106 connected in series, though they could alternatively be connected in parallel. Likewise, phase B consists of series (or parallel) connected windings 103 and 104 on diametrically opposite stator poles 107 and 108. The flux paths for phase A's stator poles 105 and 106, when excited and aligned with rotor poles 109 and 110, are identified by reference characters 111 and 112. Similarly, the flux paths for phase B's stator poles 107 and 108, when excited and aligned with rotor poles 109 and 110, are identified by reference characters 113 and 114. As may be determined by inspection of Figs. 1 and 2, stator poles 105-108 do not experience flux reversal for unidirectional current excitation of phases A and B. However, rotor poles 109 and 110 do experience flux reversal as they move from one

stator pole (say phase A's) to another stator pole having the same phase. Likewise, rotor back iron 115, which includes the regions between rotor poles 109 and 110 and around shaft 116, also undergoes flux reversal. Similarly, stator back iron segments 117 and 119 experience flux reversal. Stator back iron segment 117 is located in the region between stator poles 105 and 108, stator back iron segment 118 is located in the region between stator poles 106 and 108, stator back iron segment 119 is located between stator poles 106 and 107, and stator back iron segment 120 is located between stator poles 105 and 107.

The above-described flux reversals create: (i) forces in the opposite direction for each flux reversal, thereby causing stator acceleration and, hence, higher acoustic noise generation; and (ii) increased core losses.

SUMMARY OF THE INVENTION

An object of the present invention is to overcome the above-described problems and limitations of the related art.

Another object of the invention is to provide a two-phase switched reluctance machine (TPSRM) that eliminates electromagnetic flux reversals in the ferromagnetic or iron back material of its stator.

Still another object of the invention is to provide a TPSRM that limits the number of electromagnetic flux reversals

in the ferromagnetic or iron back material of its rotor to one per revolution of the rotor.

A further object of the invention is to provide a TPSRM that reduces acoustic noise generation at high operating speeds.

A further object of the invention is to provide a TPSRM that reduces core losses.

These and other objects of the invention may be achieved in whole or in part by a TPSRM that includes a stator, having a plurality of poles and a ferromagnetic or iron back material, and a rotor having a plurality of poles and a ferromagnetic or iron back material. A current flowing through coils wound around a first set of the plurality of stator poles induces a flux flow through the first set of stator poles and portions of the stator back material during a first excitation phase. A current flowing through coils wound around a second set of the plurality of stator poles induces a flux flow through the second set of stator poles and portions of the stator back material during a second excitation phase. The numbers of stator and rotor poles are selected such that substantially no flux reversal occurs in any part of the stator back material as a result of transitioning between the first and second excitation phases.

The objects of the invention may also be achieved in whole or in part by a TPSRM that includes a stator, having a plurality of poles and a ferromagnetic or iron back material;

and a rotor having a plurality of poles and a ferromagnetic or iron back material. A current flowing through coils wound around a first set of the plurality of stator poles induces a flux flow through the first set of stator poles and portions of the stator back material during a first excitation phase. A current flowing through coils wound around a second set of the plurality of stator poles induces a flux flow through the second set of stator poles and portions of the stator back material during a second excitation phase. The numbers of stator and rotor poles are selected such that a flux induced by each of the first and second excitation phases flows through a path encompassing about two-thirds of the circumference of each of the rotor and stator back materials.

The objects of the invention may be further achieved in whole or in part by a method of operating a TPSRM that includes: (1) inducing an electromagnetic flux to flow through a first set of poles of a stator of the TPSRM during a first excitation phase, (2) inducing an electromagnetic flux to flow through a second set of poles of the stator during a second excitation phase, and (3) transitioning between the first and second excitation phases without creating a substantial flux reversal in a ferromagnetic or iron back material of the stator.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the present invention will now be further described in the following paragraphs of the specification and may be better understood when read in conjunction with the attached drawings, in which:

Fig. 1 illustrates a related art TPSRM having 4 stator poles and 2 rotor poles and the TPSRM's flux paths when phase A is excited;

Fig. 2 illustrates the TPSRM of Fig. 1 and its flux paths when phase B is excited;

Fig. 3A illustrates a 6/9 TPSRM having its phase A poles excited when these poles are aligned with poles of the TPSRM's rotor;

Fig. 3B illustrates the normal forces produced at each of the phase A stator poles, of Fig. 3A, when phase A is excited;

Fig. 4A illustrates the 6/9 TPSRM of Fig. 3 when the TPSRM's phase B poles are excited and aligned with poles of the TPSRM's rotor;

Fig. 4B illustrates the normal forces produced at each of the phase B stator poles of Fig. 4A when phase B is excited;

Fig. 5 illustrates representative waveforms of the flux density flowing through elements of the TPSRM illustrated in Figs. 3A and 4A;

Fig. 6 illustrates a representative torque versus rotor position characteristic for the TPSRM illustrated by Figs. 3A and 3B;

Fig. 7 illustrates a TPSRM having contoured rotor poles in which the radial length of each rotor pole decreases as the distal end curvature is traversed from one side to the other;

Fig. 8 illustrates a torque versus rotor position graph for the TPSRM of Fig. 7;

Fig. 9A illustrates a rotor or stator pole whose distal end face is shaped to induce a non-uniform flux density flow through the pole; and

Fig. 9B illustrates a rotor pole that is slotted to induce a non-uniform flux density flow through the rotor pole.

DETAILED DESCRIPTION OF THE INVENTION

The present invention endows the machine designer with a degree of freedom for enhancing machine performance by providing an additional variable for reducing core losses. The invention completely eliminates flux reversals in the stator back iron of a two-phase switched reluctance machine (TPSRM) and reduces the number of flux reversals in the rotor back iron, thereby reducing the flux density in these iron parts and controlling both the hysteresis and eddy current losses in them. This leads to minimization of the core losses in the machine and maximization of its operational efficiency. Further, by eliminating the stator flux reversals, the acoustic noise generated by such reversals is minimized.

The invention uniquely provides a two-thirds utilization ratio of the stator to rotor back iron sections serving to

convey flux at any given time of the TPSRM's operation, so as to reduce the size of the flux path. TPSRMs having a combination of six stator poles and three rotor poles (i.e., a 6/3 TPSRM) or six stator poles and nine rotor poles (i.e., a 6/9 TPSRM) provide such a two-thirds utilization ratio and its resultant smaller flux path. A smaller flux path requires less magneto motive force (mmf), thereby providing higher efficiency operation. Furthermore, the core losses in the lamination material decrease, since core losses are related to the volume of the material that is covered by the flux path.

Fig. 3A illustrates a 6/9 TPSRM having its phase A poles excited when these poles are aligned with poles of the TPSRM's rotor. Fig. 4A illustrates the 6/9 TPSRM of Fig. 3 when the TPSRM's phase B poles are excited and aligned with poles of the rotor. The stator poles excited during phase A are stator poles A1, A2 and A3, and the stator poles excited during phase B are stator poles B1, B2 and B3. Stator poles A1-A3 and B1-B3 are excited by coils 301-303 and 304-306, respectively, wound around the poles. In an exemplary embodiment, the coils on each stator pole have an equal number of turns but may carry differing currents, though other configurations are possible. For the exemplary embodiment, the current in stator poles A1 and B1 is assumed to be I amperes. Coils 302, 303 on stator poles A2 and A3 are connected in parallel, so that the current coming into coil 301 of stator pole A1 is divided into equal parts for coils 302, 303 and has a value of I/2.

Similarly, for coil 304 on stator pole B1, a current of I amperes passes through stator pole B1 and is divided equally into parallel coils 305, 306, wound on stator poles B2 and B3, so that they pass a current of I/2. With this configuration, the magneto motive force (mmf) provided by the currents flowing through coils 301, 304 of stator poles A1 and B1, respectively, is NI and is NI/2 for each of stator poles A2, A3, B2, and B3. The direction of the currents entering coils 301-306 of stator poles A1-A3 and B1-B3, as indicated by flux paths 307-310 and 407-410 respectively, implies a positive value mmf being exerted by each of stator poles A1 and B1 and a negative value mmf being exerted by each of stator poles A2, A3, B2, and B3.

Fig. 3B illustrates the normal forces produced at each of the phase A stator poles of Fig. 3A, when phase A is excited. Fig. 4B illustrates the normal forces produced at each of the phase B stator poles of Fig. 4A, when phase B is excited. As illustrated by Figs. 3B and 4B, the normal (i.e., radial) forces F_{A1R1}, F_{A2R4}, and F_{A3R7} for stator poles A1-A3 combine to produce a vector sum of zero when phase A is excited and, similarly, normal forces F_{B1R5}, F_{B2R8}, and F_{B3R2} for stator poles B1-B3 combine to produce a vector sum of zero when phase B is excited. Therefore, the resultant normal force exerted on the rotor by the stator is zero for all periods of operation. Moreover, since the individual radial forces pull in three different directions for each of phases A and B, they act to

prevent the ovalization of the stator and, hence, mitigate stator acceleration induced by the transitions between the excitation of phases A and B. As a result, the invention reduces acoustic noise in TPSRM 300.

In the related art TPSRM 100 illustrated by Figs. 1 and 2, the generated normal forces for each of the phase A and B excitations have the same magnitude and opposite directions (i.e., a 180 degree directional separation). These equal and oppositely directed forces induce an ovalization of the stator, as the resultant normal force is cancelled through the stator and rotor bodies. Moreover, since the phase A and B excitations induce ovalizations at right angles to one another, the stator is accelerated between phase excitations and, thereby, produces acoustic noise.

Another advantage of the invention results from the characteristic flux flow it produces in the back iron 311 of the stator, in particular. Referring to Fig. 3A, four flux paths exist in stator back iron 311. These four paths are flux path 307 between stator poles A3 and B2, flux path 308 between stator poles B2 and A1, flux path 309 between stator poles A2 and B3, and flux path 310 between stator poles B3 and A1. Four flux paths are also shown in Fig. 4A. These flux paths are flux path 407 between stator poles A3 and B2, flux path 408 between stator poles A3 and B1, flux path 409 between stator poles A2 and B3, and flux path 410 between stator poles B1 and A2. Of these eight flux paths, only flux paths 307,

309 and flux paths 407 and 409, respectively, overlap in the stator's back iron. Flux paths 307, 309 correspond to the excitation of phase A and flux paths 407, 409 correspond to the excitation of phase B. As may be seen by inspection of Figs. 3A and 4A, flux paths 307 and 407 have the same direction of travel through the portions of stator back iron 311 through which both paths flow. Similarly, flux paths 309 and 409 have the same direction of travel through the portions of stator back iron 311 through which these flux paths flow. Therefore, no portion of stator back iron 311 experiences flux reversal during the operation of TPSRM 300. The absence of flux reversal in stator back iron 311 reduces core losses.

Still another advantage of the invention is that the flux reversal in segments of rotor back iron 312 occurs only once per revolution, which also reduces core losses. Stator poles A1-A3 and B1-B3 also do not experience any flux reversal, though rotor poles R1-R9 do.

Fig. 5 illustrates representative waveforms of the flux density flowing through elements of TPSRM 300, illustrated in Figs. 3A and 4A. In Fig. 5, the flux density waveforms for stator poles A1 and B2 are indicated by A1 and B2, respectively, and the flux density waveform for rotor pole R1 is identified by R1. The nomenclature R1R9 refers to the rotor back iron region between rotor poles R1 and R9. Similarly, the nomenclature B2A1 and B2A3 refer to the region between stator poles B2 and A1 and the region between stator

poles B2 and A3, respectively. As may be determined by inspection of Fig. 5, a flux density reversal occurs in rotor back iron 312 once per revolution, but no flux density reversal occurs in stator back iron 311.

In Fig. 5, the magnitude value B_m indicates the maximum flux density experienced by stator poles A1 and B1. Only stator poles A1 and B1 carry the maximum flux density value B_m. All other stator poles A2, A3, B2, and B3 carry a maximum flux density of $B_m/2$. As a result, all stator poles other than A1 and B1 can be half the size of stator poles A1 and B1, as each carries only half the flux of these poles. A considerable cost saving and weight reduction can be achieved with this arrangement. This may matter in aerospace applications where weight and volume minimization are critical factors in the selection of an electric machine.

The present invention eliminates flux reversals in the stator back iron and reduces or minimizes flux reversals in the rotor back iron. The stator back iron is defined for this invention as being all iron or ferromagnetic components in the stator, except the stator pole components, that convey the flux flowing through the rotor and stator. Because there are no flux reversals in the stator back iron, the hysteresis and eddy current losses in the iron decrease significantly, thus enhancing the efficiency of the machine.

In the rotor back iron (i.e., the back iron between adjacent rotor poles), the flux reversal occurs only once per

rotor revolution, which is much less than occurs in conventional machines. For example, in a conventional 6/4 SRM, flux reversal in the rotor back iron may occur six times per rotor revolution, as described in Chapter 3 of Switched Reluctance Motor Drives, by R. Krishnan, CRC Press, 2001, which is hereby incorporated in its entirety into this specification. Four flux reversals occur in one revolution of the rotor in a conventional three-phase 12/8 machine.

Fig. 6 illustrates a representative torque versus rotor position characteristic for the TPSRM illustrated by Figs. 3A and 3B. As may be seen by inspection of Fig. 6, there are rotor positions for which the torque 601, 602 produced by each of phases A and B is zero. To produce a non-zero torque at all rotor positions, the rotor poles can be slotted, contoured, air-gap stepped, etc.

Fig. 7 illustrates a TPSRM having contoured rotor poles in which the radial length of each rotor pole decreases as the distal end curvature is traversed from one side to the other. Fig. 8 illustrates a torque versus rotor position graph for the TPSRM of Fig. 7. The torque for phase A is identified by reference character 801 and that for phase B is identified by reference character 802. The contouring of rotor pole 701 provides a non-uniform air gap across the pole face. As a result, the combined torque generated by TPSRM 700 has a non-zero value, considering both phases of the machine, at all times. This feature is crucial for supporting a self-starting

capability for TPSRM 700 in both rotational directions of the shaft.

The present invention provides a force distribution similar to that of three phase ac machines, by distributing a stator current distribution among three windings. The three windings may constitute one phase of the SRM, as illustrated in Figs. 3A and 4A. Alternatively, the SRM may have multiples of three windings in a phase with other combinations of total stator and rotor poles. The rationale for such a force distribution is that the normal forces are cancelled and uniformly distributed about the circle of rotation. Furthermore, the tangential forces can be distributed over two thirds of the periphery as opposed to only half the periphery, such as occurs where only two diametrically opposite poles contribute to the entire tangential force.

Fig. 9A illustrates a rotor or stator pole whose distal end face is shaped to induce a non-uniform flux density flow through the pole. Fig. 9B illustrates a rotor pole that is slotted to induce a non-uniform flux density flow through the rotor pole. In Fig. 9A, rotor or stator pole 900 is shaped so that its distal end face has a non-uniform radius from the rotational axis of the rotor. In Fig. 9B, slots 911 are formed in rotor pole 910. With stator pole shaping or rotor pole shaping or slotting, or some combination thereof, the present invention can operate in both the clockwise and counter-clockwise directions with full four-quadrant

capability, thereby providing a bidirectional start and run capability using only two phases.

The embodiment of the invention illustrated in Figs. 3A and 4A is only one of many embodiments of the invention. Other embodiments may have different combinations of stator and rotor poles, such as the combinations of 6/3, 6/15, etc. The invention completely eliminates flux reversals in the stator back iron and reduces or minimizes the flux reversals in the rotor back iron to one reversal for each rotor revolution.

There are many advantages to having zero flux reversals in the stator back iron. These include: (1) reduced core losses and, hence, higher operating efficiency of the machine, (2) reduced vibration in the stator back iron and, hence, lower acoustic noise generated in the machine, and (3) a lower amount of required excitation, since there is no flux reversal in the machine, and hence higher operating efficiency.

Similarly there are advantages to having only one flux reversal per revolution in the rotor back iron of the machine. These advantages include reduced core losses, reduced excitation requirements, and reduced vibration induced by the rotor.

The present invention includes the unique pole combination of 6/9 for the stator and rotor with concentric windings for a two phase switched reluctance machine and its derivatives using the same principle of no flux reversals in

the stator back iron. The stator poles may have differing numbers of winding turns around each pole of one phase of the machine, so as to distribute the normal and tangential forces as desired. Also, the winding currents on each pole can be controlled independently of other winding currents, thereby individually controlling the normal force around the periphery of the machine to produce a frictionless SRM. Furthermore, the TPSRM may be operated with the power converter topologies, described in Applicant's co-pending applications, that use either one controllable switch or two controllable switches for the control of currents and voltages in the windings of the machine for the two phases of the machine.

The foregoing description illustrates and describes the present invention. However, the disclosure shows and describes only the preferred embodiments of the invention, but it is to be understood that the invention is capable of use in various other combinations, modifications, and environments. Also, the invention is capable of change or modification, within the scope of the inventive concept, as expressed herein, that is commensurate with the above teachings and the skill or knowledge of one skilled in the relevant art.

The embodiments described herein are further intended to explain best modes known of practicing the invention and to enable others skilled in the art to utilize the invention in these and other embodiments, with the various modifications that may be required by the particular applications or uses of

the invention. Accordingly, the description is not intended to limit the invention to the form disclosed herein.

Apparatus and Method that Prevent Flux Reversal in the Stator Back Material of a Two-Phase SRM (TPSRM)

Appendix A

TWO PHASE SWITCHED RELUCTANCE MACHINE/MOTOR (SRM) AND CONVERTER AND ROTOR POLE SLOTTING STRUCTURE FOR SUCH

SUMMARY OF THE INVENTION

The present invention is described in conjunction with twenty-one separate embodiments, discussed below. All of the reference materials identified herein-below are hereby incorporated by reference. Additionally, the provisional applications identified by application numbers 60/382,608, 60/382,609, and 60/382/610 are hereby incorporated into this application by reference.

DRAWINGS

Several embodiments of the present invention will now be further described in the following paragraphs of the specification and may be better understood when read in conjunction with the attached drawings, in which:

Fig. 1 illustrates a single controllable switch and diode power converter for a one or two phase SRM according to a first embodiment of the invention;

Fig. 2 illustrates a single controllable switch and diode power converter for a one or two phase SRM according to a second embodiment of the invention, in which phase B has no associated diode;

Fig. 3 illustrates a single controllable switch and diode power converter for a one or two phase SRM according to a third embodiment of the invention;

Fig. 4 illustrates a single controllable switch and diode power converter for a one or two phase SRM according to a fourth embodiment of the invention;

Fig. 5 illustrates a single controllable switch and diode power converter for a one or two phase SRM according to a fifth embodiment of the invention;

Fig. 6 illustrates a single controllable switch and diode power converter for a one or two phase SRM according to a sixth embodiment of the invention;

Fig. 7 illustrates a single power switch for a two phase SRM and PM brushless dc machine according to a seventh embodiment of the invention;

Fig. 8 illustrates a single power switch for a two phase SRM and PM brushless dc machine according to an eighth embodiment of the invention;

Figs. 9a and 9b illustrate a single power switch for a two phase SRM and PM brushless dc machine according to a ninth embodiment of the invention;

Fig. 10 illustrates a single power switch for a two phase SRM and PM brushless dc machine according to a tenth embodiment of the invention;

Fig. 11a illustrates a two-phase SRM with six stator and nine rotor poles according to an eleventh embodiment of the invention;

Fig. 11b illustrates a normal force diagram corresponding to Fig. 11a;

Fig. 12a illustrates the two-phase SRM of Fig. 11a when phase B is excited through the alignment of its associated poles;

Fig. 12b illustrates a normal force diagram corresponding to Fig. 12a;

Fig. 13 illustrates flux density distribution waveforms corresponding to the device illustrated in Figs. 11 and 12;

Fig. 14 illustrates the structure of a slotted rotor pole according to a twelfth embodiment of the invention;

Fig. 15 illustrates shifted slots in the rotor poles to provide bi-directional starting according to the twelfth embodiment of the invention;

Fig. 16 illustrates a slotted rotor structure with alternate arrangement of the slots, with respect to the center lines of

opposite poles, according to a thirteenth embodiment of the invention;

Fig. 17 illustrates a slotted rotor structure that provides an asymmetric air gap and an asymmetric torque profile for starting according to a fourteenth embodiment of the invention;

Fig. 18 illustrates another arrangement of the rotor slots in a two-phase SRM according to the fourteenth embodiment of the invention;

Fig. 19 illustrates a rotor pole with both rectangular and curved rotor slots according to a fifteenth embodiment of the invention;

Fig. 20 illustrates a slotted rotor pole, having slots separated by lamination material, according to a sixteenth embodiment of the invention;

Figs. 21 and 22 illustrate alternative slotting structures that may be applied to the twelfth through sixteenth embodiments;

Fig. 23 illustrates a two phase SRM with four poles in the corners of a square lamination according to a seventeenth embodiment of the invention;

Fig. 24 illustrates a two phase SRM with four poles in the middle of the square lamination according to a seventeenth embodiment of the invention;

Fig. 25a illustrates the difference between the pole lengths of middle and corner placed poles in circular and square stator laminations, respectively;

Fig. 25b illustrates a change in stator pole length versus k, according to the seventeenth embodiment of the invention;

Fig. 26 illustrates a wire wrap with a weld in the middle point according to the seventeenth embodiment;

Fig. 27 illustrates a stator coli securing method for stator poles in the middle of the square lamination;

Fig. 28 illustrates a two phase PMBDCM with four stator and rotor poles according to an eighteenth embodiment of the invention;

Fig. 29a illustrates waveforms for a two-phase PMBDCM with 180 electrical degrees phase between their emfs;

Fig. 29b illustrates a two-phase PMBDCM with 90 electrical phase between their emfs;

Fig. 30 illustrates a two phase PMBDCM with 90 degrees phase shift between coils according to a nineteenth embodiment of the invention;

Fig. 31 illustrates a two phase PMBDCM with spatial shift of more than 90 degrees between phases according to the nineteenth embodiment of the invention;

Fig. 32 illustrates a winding diagram for the two phase PMBDCM of the nineteenth embodiment.

Fig. 33 illustrates the flux linkages and induced emf waveforms of the two phase PMBDCM, having the spacial shift of 90 electrical degrees, according to the nineteenth embodiment of the invention;

Fig. 34 illustrates a two phase PMBDCM with square outer frame according to the nineteenth embodiment of the invention;

Fig. 35 illustrates a single power switch converter for a two phase PMBDCM according to a twentieth embodiment of the invention.

Fig. 33 illustrates the flux linkages and induced emf waveforms of the two phase PMBDCM, with more than 90 degrees spatial shift between two phases, according to a twenty-first embodiment of the invention; and

Figs. 37-49 illustrate additional features of the nineteenth through twenty-first embodiments of the invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

FIRST EMBODIMENT

Description

The first embodiment of the invention is a Single Switch Two Phase Switched Reluctance Machine/Motor (SRM) Converter. This embodiment is described below.

An electronic power converter for driving a two phase switched reluctance motor (SRM) is disclosed with unique features of having only one controllable power switch and one diode, as against two or more controllable power switches and two or more diodes. Sometimes, the second phase of the 2 phase SRM may not be used to produce motive force but may serve to assist starting of the machine and for providing a means for enabling the estimation of rotor position for control purposes. It will be described separately. But also, the second phase may also be used to produce the motive power in some other applications. Regardless of the use of the second phase of the SRM, the invention covers both the cases. The present invention includes multiple circuit topology variations of the single switch two phase SRM converter topology and identifies single switch power converter topologies for two phase SRMs as well as permanent magnet (PM) brushless dc machines.

The power electronic converter required to drive a two phase SRM usually requires more than two controllable switches and more than two diodes. The circuits requiring two controllable switches and diodes have the disadvantage of high power loss, low efficiency or bifilar winding in the machine thereby reducing the power density of the machine. The existing solutions are not therefore attractive from the considerations of high efficiency operation, full range of speed control and compactness in the converter's packaging and most of all the overall cost of the system.

Fig. 1, which was previously disclosed in the provisional application identified by attorney docket number L1081.02101, overcomes all these disadvantages with a new topology that uses one controllable switch and one (fast switching diode) or optionally

two diodes (one fast switching and the other slow). In shrinking the number of controllable switches to one and the diode to one, the power converter's cost has become the lowest compared to all other topologies that are currently available.

We call one phase winding as main (phase A) and the other winding as auxiliary winding (phase B) (even though both may be termed main winding 1 and 2). The excitation of main winding 1 leads to the auxiliary capacitor (Cb) being charged up. The energy stored in the auxiliary capacitor circulates a current in the auxiliary winding. The energy flow in the capacitor and hence in the auxiliary phase is dependent on the main phase winding's energy flow and, therefore, its duty cycle. Higher the speed, the duty cycle of the controllable switch increases thereby increasing the voltage applied to the main winding and therefore, less and less charging of the auxiliary capacitor and hence less power to the auxiliary winding. During these times, the machine behaves as though it is a single phase SRM with the auxiliary phase winding serving as a window to find the rotor position of the machine through its inductance which can be obtained from its current and voltage waveform or by some other means. During the low speed regime, both phases are active and produce motive power and, therefore, the machine serves as a two phase SRM. This resembles a capacitor start and capacitor run single phase induction motor. Note that such a single phase induction motor has two phase windings.

Some features of this embodiment include:

1. One controllable switch and one diode (or optionally two diodes) for controlling a two phase SRM.

2. The auxiliary capacitor serves as a snubber also in addition to its function as an energy source for feeding the auxiliary phase.

3. The circuit has minimum power switches and minimum components.

4. The controllable switch does not require isolated power supply as the emitter of that switch is connected to the negative rail of the dc power supply resulting in significant savings in the gate control circuitry cost.

5. For low power applications, a single rectifier diode rectifier to provide the dc source voltage from an ac source absolutely makes this converter the lowest cost and lowest component based power converter topology for any SRM drive system and for that matter even for a PM brushless dc motor drive system.

6. By making this a single controllable switch based converter, this drive system compares favorably with the single switch chopper based brush dc and universal motor drive systems. This fact alone answers the challenge for the first time that a brushless motor drive with one controllable switch is feasible and, therefore, can be a powerful competitor to a vast number of applications in the market place today.

7. The control is the simplest as there is only one switch to be controlled and this fact contributes to the most elementary control circuit for its speed and current control.

8. The fact that the invention drives a 2 phase SRM may be used to develop a self- starting single phase SRM with the self starting feature provided by the auxiliary winding to start it from any rotor position at rest.

9. This converter topology can be used for any number of even phase SRMs.

10. This converter topology can also be used for half wave controlled PM brushless dc machines with even stator phases.

A number of topological variations are possible with this first embodiment and some of these are discussed in detail below. These variations of the first embodiment are identified as the

second through sixth embodiments. The operation of these embodiments would be recognized by artisans of this field based upon the description provided for the first embodiment. Therefore, only the significant differences between the first and the second through sixth embodiments will be discussed below. Each of these embodiments is especially useful for application in the low cost high volume appliance market.

SECOND EMBODIMENT

Description

Fig. 2 illustrates a second embodiment of the Single Switch Two Phase SRM Converter. In this illustration, phase B represents the auxiliary phase winding. The second embodiment is similar to the first embodiment except that there is no diode in the path of the auxiliary capacitor. The second embodiment has advantages similar to those of the first embodiment but has the added advantages of:

1. A reduction of one more diode for operation of the circuit.

2. The auxiliary capacitor will be charged and balanced to the value of the dc link voltage thereby excessive charge will not accumulate in the auxiliary capacitor.

3. The time for the current to reduce is much faster as there is only L and C circuit when the main switch is turned off.

THIRD EMBODIMENT

Description

Fig. 3 illustrates a third embodiment of the Single Switch Two Phase SRM Converter. The major advantages of this embodiment are:

1. When the switch is turned off, phase A charges the capacitor, Cb, without involving the dc link capacitor, Cs. The extra charge in Cb discharges to phase B and dc link capacitor

until the voltages in the dc link and auxiliary capacitor are equal.

2. It charges the auxiliary capacitor at starting, resulting in aligning rotor poles to auxiliary stator poles and thereby resulting in a favorable starting position and for excitation of phase A (the main phase).

3. It also preserves all the advantages of the first embodiment.

FOURTH EMBODIMENT

Description

Fig. 4 illustrates a fourth embodiment of the Single Switch Two Phase SRM Converter. This embodiment has advantages similar to those of the third embodiment but may require an isolated power supply or a charge pump based gate driver for the main switch.

FIFTH EMBODIMENT

Description

Fig. 5 illustrates a fifth embodiment of the Single Switch Two Phase SRM Converter. This embodiment has advantages similar to those of the third embodiment but additionally has the advantage that the diode associated with phase B prevents the flow of current in one direction. This leads to initiating current in phase A at the time of starting due to overcharging of the auxiliary capacitor.

SIXTH EMBODIMENT

Description

Fig. 6 illustrates a sixth embodiment of the Single Switch Two Phase SRM Converter. This embodiment has the advantages of the first embodiment but may also provide an advantageous starting

position, since both phases A and B are excited as the circuit is energized.

SEVENTH EMBODIMENT

Description

The seventh embodiment of the invention is a Single Power Switch for a Two Phase SRM and a Permanent Magnet (PM) Brushless Direct Current (dc) Machine (PMBDCM). This embodiment is described below.

Fig. 7 illustrates a single power switch for a two phase SRM having the least number of elements, as compared to any existing power converter topology. The illustrated topology is useful for driving a two phase SRM or a two phase permanent magnet brushless dc machine (PMBDCM). The circuit of Fig. 7 operates as follows.

The converter has only one diode for rectification of the alternating current (ac) supply voltage into a usable dc voltage for the machine shown in series with the single-phase ac source. By limiting the rectifier diodes to one only, a huge saving of the rectification stage of the power converter is achieved while reducing the power loss associated with two diodes in series required for a full wave rectification. Therefore, this rectification with one diode for low power applications serves the purpose of low cost and high efficiency of power conversion for the ac to dc stages.

The dc link is provided by the capacitor and it is softly charged as it is connected in series with the machine phases A and B. The same capacitor also provides the energy for circulating a current to the machine phases. For the dc link to machine power transfer, power switch TA controls the energy transfer from the dc link capacitor to machine phases.

The two power stages of the power converter and power control of the machine phases are described in this part of the description. Next to be considered is the operation of the power converter.

Power to machine phases A and B are transferred from the instant power switch TA is turned on. Phase A's current is determined solely by the ac source while the current in phase B is determined by the difference between the dc link voltage and the instantaneous voltage of the ac source during rectification mode of the positive half-wave. During negative half-wave of the ac source, the phase B's current is solely determined by the dc link voltage and the combined impedance of the phases A and B because of the rectification diode is open circuited. Because of the unique features of the current control possible during the positive and negative half-waves of the ac source, and by combining the A and B phases winding turns and their spatial phase shift, it is possible to produce a four-quadrant variable speed drive system with a control system as described hereinafter. When switch is turned off, note that the current in phase B circulates via phase A. The current of the phase A will flow through the ac source, rectification diode, phase A, diode Da, and dc link capacitor, Cb. Thus, the energy stored in the phase A is transferred to dc link capacitor.

Some features of this embodiment include:

1. The most minimum circuit for a four-quadrant variable speed operation of a two
phase SRM or a two phase PMBDCM drive system.

2. It uses only one controllable switch, a total of two diodes and one capacitor. This is the most minimum for a converter circuit in motor drive applications that may be found. For example, in one quadrant dc chopper drive but no ac drive has had a single switch topology providing a four-quadrant operation.

3. When a controller can be packed in a single chip, this drive system will have the most minimum and compact size for a four-quadrant drive.

A number of topological variations are possible with this seventh embodiment and some of these are discussed in detail below. These variations of the seventh embodiment are identified as the eighth through tenth embodiments. The operation of these embodiments would be recognized by artisans of this field based upon the description provided for the seventh embodiment. Therefore, only the significant differences between the seventh and the eighth through tenth embodiments will be discussed below. Each of these embodiments is especially useful for application in the high volume appliance market.

EIGHTH EMBODIMENT

Description

Fig. 8 illustrates a Single Power Switch for a Two Phase SRM and a PMBDCM according to an eighth embodiment of the invention. As illustrated, a diode in the path of the phase B winding restricts the path of charging of capacitor through phase A only. This can have some advantages in control as the phase B is ideally placed for producing torque and shaft rotation at the time of the start itself.

NINTH EMBODIMENT

Description

Figs. 9a and 9b illustrate a Single Power Switch for a Two Phase SRM and a PMBDCM according to a ninth embodiment of the invention. As illustrated, only the dc source will have an influence in controlling both phases' currents.

TENTH EMBODIMENT

Description

Fig. 10 illustrates a Single Power Switch for a Two Phase SRM and a PMBDCM according to a tenth embodiment of the invention.

Some features of the seventh through tenth embodiments include:

1. A single controllable switch for controlling energy in both phases of a SRM or PMBDCM drive system.

2. A single diode for rectification of ac to dc voltage in combination with single power switch for controlling currents in both phases of a SRM or a PMBDCM.

3. A single diode for freewheeling of currents when the controllable switch is turned off in a two-phase SRM or PMBDCM drive.

4. A single dc link capacitor in combination with a two-phase SRM or PMBDCM drive with one controllable switch for one, two or four-quadrant variable speed operation.

5. A combination of single dc link capacitor, one rectifying diode, one freewheeling
diode and one controllable switch to control a two phase SRM or a two phase PMBDCM drive in variable speed operation.

6. A combination of a single dc link capacitor, one rectifying diode, one freewheeling diode and one controllable switch to control a two phase SRM or a two phase PMBDCM drive in variable speed operation having one-quadrant, or two-quadrant or four- quadrant regimes of operation.

7. A combination of single dc link capacitor, one rectifying diode, one blocking diode, one freewheeling diode and one controllable switch to control a two phase SRM or a two phase PMBDCM drive in variable speed operation having one-quadrant, or two-quadrant or four- quadrant regimes of operation.

8. A combination of a single dc link capacitor, one rectifying diode, one freewheeling diode and one controllable

switch to control a two phase SRM or a two phase PMBDCM drive in variable speed operation having one-quadrant, or two-quadrant or four- quadrant regimes of operation in such a way that the phase currents are not directly controlled by the ac source's instantaneous voltage.

9. A combination of the machine inductances and the dc link capacitor in such a way that the initial charging from the ac source is done softly and this combination inherently to serve as a dc link filter combination while doing other functions.

10. Control of the phase currents is impacted by the embodiments and accordingly such modes of operation in combination with each embodiment are disclosed here.

11. Endows a brushless drive, such as an SRM or PMBDCM, to work with minimum component topology and yet provide a four-quadrant operation.

ELEVENTH EMBODIMENT

Description

The eleventh embodiment of the invention is a Two Phase Switched Reluctance Machine with No Flux Reversals in the Stator Back Iron. Fig. 11a illustrates a two-phase SRM with six stator and nine rotor poles according to the eleventh embodiment of the invention. Phase A is excited when the poles are aligned. Fig. 11b illustrates a normal force diagram corresponding to Fig. 11a. Fig. 12a illustrates the two-phase SRM of Fig. 11a when phase B is excited through the alignment of its associated poles. Fig. 12b illustrates a normal force diagram corresponding to Fig. 12a.

Some of the features provided by this embodiment are the following:

1. No flux reversals in the stator back iron and reduced or minimized flux reversals in the rotor back iron. The back irons are defined as all the iron paths in the stator except that of the

stator poles. The compelling reason for this arrangement is that with no flux reversals, the hysteresis and eddy current losses in the iron decrease significantly thus enhancing the efficiency of the machine operation.

In the rotor back iron (i.e., between two adjacent rotor poles), the flux reversal occurs only once in a rotor revolution. This is much smaller than in the related art machines. For example, in a related art 6/4 SRM, the flux reversals in the rotor back iron can be six times in one rotor revolution and refer to flux density waveforms in Chapter 3 of R. Krishnan, "Switched Reluctance Motor Drives", CRC Press, 2001.

In the rotor poles, only one flux reversal per rotor revolution occurs in the present invention whereas in the 3 phase 12/8 machine, there are four flux reversals in one revolution of the rotor.

2. It provides a force distribution similar to that of three phase ac machines by having a stator current distribution between three windings (constituting one phase of the SRM in some implementations but may contain multiples of three windings in a phase with other combinations of the poles) very similar to that of the three phase ac machines. The rationale for such a force distribution is that the normal forces are cancelled and that too uniformly and tangential forces can be distributed over two third of the periphery as against only half the periphery in the case of two diametrically opposite poles contributing to the whole tangential force.

3. To provide higher reliability by having a higher number of windings in parallel in each phase. In the illustrated case, we have three windings per phase in parallel as against two in related art SRMs. {Note that in a 12/8 SRM, the reliability and iron utilization may be higher but flux reversals exist in the stator

back iron and with many more flux reversals in the rotor back iron).

4. To provide a bi-directional start and run capability and performance with two phases only. With stator pole shaping and or rotor pole shaping or rotor slotting as described in many of the embodiments disclosed herein, the eleventh embodiment can operate in both directions (clockwise (CW) and counter-clockwise (CCW)) with full four-quadrant capability.

The embodiments shown in Figs. 11 and 12 are only one set of possible implementations of this embodiment. Other possible combinations of the stator poles and rotor poles include 6/18, 6/3, 6/15, etc. It is noted that many more combinations exist and are included in this invention. The invention completely eliminates flux reversals in the stator back iron and reduces or minimizes the flux reversals to one in the rotor back iron for each rotor revolution.

Fig. 13 illustrates flux density distribution waveforms corresponding to the device illustrated in Figs. 11 and 12. As may be seen by inspection, there are no flux reversals in the stator back iron. There are many advantages to having zero flux reversals in the stator back iron. They are:

1. Reduced core losses and hence resulting higher operation of the machine.

2. Reduced vibration in the stator back iron and hence lower acoustic noise generated in the machine which is a great advantage particularly in SRMs, since they are plagued with that problem.

3. Lower excitation requirement as there is no flux reversal in the machine and hence higher efficiency in its operation.

Similarly there are advantages to having only one flux reversal per revolution in the rotor back iron of the machine, as opposed to the many flux reversals in the rotor back iron of related art machines. Again, the advantages are reduced core

losses, reduced excitation requirements, and possibly reduced vibration induced by the rotor.

Also covered in the present invention is the unique pole combination of 6/9 for the stator and rotor with concentric windings for a two-phase switched reluctance machine and its derivatives using the same principle of no flux reversals in the stator back iron.

The eleventh embodiment is especially useful for application in the high volume appliance market. Further implementations of this embodiment include the following:

1. Various number of turns of winding in each pole of one phase of the machine in order to distribute the normal and tangential forces to desired levels.

2. Winding currents on each pole can be controlled independently of other winding currents thus individually controlling the normal force around the periphery of the machine resulting in frictionless SRMs. This is an advantage of the present invention.

3. The eleventh embodiment can also use all of the power converter topologies embodiments disclosed herein using either one controllable switch or two controllable switches for the control of currents and voltages in the windings of the machine for a set of two phases of the machine.

4. The eleventh embodiment can also be combined with an axial SRM of different pole numbers or of the same pole numbers that can be housed in the rotor and end bells for the rotor and stator of the axial field machine, respectively. Such a machine structure leads to high reliability in operation and high power density.

TWELFTH EMBODIMENT

Description

The twelfth embodiment of the invention is a Rotor Pole Slotting Structure for Self-Starting of a Two Phase SRM. This embodiment is described below.

Generally, a two phase SRM does not produce non-zero electromagnetic torque at all rotor positions. There are rotor positions when the two phase SRM has zero torque instances and when such positions are encountered at standstill, it is impossible to start the machine. Such positions are many in a two phase SRM. There have been attempts to overcome such a problem, but many of these attempted structures produce an unevenness in the mechanical structure resulting in a non-uniform air gap when the stator and rotor poles align and they also seem to be prone to normally induced forces and hence may have a slightly higher acoustic noise. This is yet to be proved but can be inferred from the electromagnetic structure and the slope of the inductance curves of these machines.

More specifically, some related art structures have rotor poles extending on one side in regard to their pole shoes, providing a preferential running in one direction. This has the disadvantage of high acoustic noise generation in the machine and a flimsy and fragile rotor construction due to the overhanging poles on one side. Therefore, a better and an improved method of producing an electromagnetic torque at all rotor positions (either with one or the other phase) is desired.

Fig. 14 illustrates the structure of a slotted rotor pole. This structure is highly desirable because it is easy to punch.

Fig. 15 illustrates shifted slots in the rotor poles to provide bi-directional starting according to the twelfth embodiment of the invention. This structure provides an electromagnetic torque for all rotor positions of a two phase SRM that can also be used as a single phase SRM. Without affecting the uniform air gap between the stator and rotor poles during their alignment, an

equivalent skewing of flux linkages can be produced by having a slot in the rotor poles. The slots can have a variety of shapes and one such shape is shown in Fig. 15. By having the slot, the preferred path for the flux to flow from a stator pole to rotor pole and vice versa is achieved. Making the slot axis uneven toward one side reduces the flow of flux on that side by increasing the air gap reluctance and increases the flux on the other side with more iron and reducing the net air gap faced by the flux path. This tends to provide a preferential starting direction for the rotor.

The slotting on the adjacent rotor poles have opposite slot axes, i.e., the slot axis of one rotor pole is made closer to its right side while the adjacent rotor pole will have the slot axis towards his left side of the rotor pole. This provides the necessary high rate of change of flux linkages, the first one in the counter clockwise direction and the latter in the clockwise direction resulting in higher torque also in respective direction and hence rotation in these directions. Note that such shifting of rotor pole slotting axis provides a beneficial effect not only on torque at all rotor positions and directional choice of running, it also removes some amount of iron the rotor poles resulting in lighter rotor and hence lower rotor inertia. This has advantages in high performance applications where to torque to inertia ratio (which is also the acceleration of the machine) has to be maximized to reduce the process cycle times. It can also have applications in aerospace where low weight is of prime concern and choice. Many choices of rotor slotting are shown in attachments. They all have the same effect of providing the unequal resultant air gap when stator and rotor poles align and hence directional torque producing capability for starting in both directions.

A number of variations to this twelfth embodiment are discussed below. These variations are identified as the thirteenth

through sixteenth embodiments. Each of these embodiments is especially useful for aerospace, fan, and pump applications.

THIRTEENTH EMBODIMENT

Description

Fig. 16 illustrates a slotted rotor structure with alternate arrangement of the slots, with respect to the center lines of opposite poles, according to a thirteenth embodiment of the invention. This structure has the same slotting structure as the twelfth embodiment but is positioned symmetrically to the center line of the diametrically opposite rotor poles.

As illustrated by Fig. 16, the slots are on opposite ends of the diametrically opposite rotor poles. Two rotor poles' slots face each other while the other pair's slots are randomly placed. There is a complete balance of the rotor with this arrangement.

Note that the same approach is applicable for any number of machine phases with any number of rotor pole and stator pole combinations. The distinct advantage of the present arrangement can be seen in the torque being non-zero at all rotor positions when both the phases are considered. Further it may be noted that there is equal distribution of rotor weight on the shaft and it is symmetric.

FOURTEENTH EMBODIMENT

Description

Fig. 17 illustrates a slotted rotor structure that provides an asymmetric air gap and an asymmetric torque profile for starting according to a fourteenth embodiment of the invention. The rotor pole may be slotted alternately to provide torque asymmetry such that there is non-zero torque for any rotor position. The slot is cut on the top of the rotor pole to have the shape of the rotor arc but on the bottom it is tapered out to increase the effective air

gap. Note that the center of the rotor pole and the center of the rotor slot do not coincide, so as to provide the asymmetry with respect to phases A and B stators.

Fig. 18 illustrates another arrangement of the rotor slots in a two-phase SRM according to the fourteenth embodiment of the invention. As illustrated, the rotor poles are punched as shown in Fig. 17 and then placed similar to the arrangement in the thirteenth embodiment so that the rotor weight is symmetrically distributed.

FIFTEENTH EMBODIMENT

Description

Fig. 19 illustrates a rotor pole with both rectangular and curved rotor slots according to a fifteenth embodiment of the invention. Rotor slots that can combine a circumscribed arc and rectangular or any other regular or irregular shaped but circumscribed can be placed off center of the rotor pole to create an asymmetric air gap to yield an asymmetric flux linkage distribution with regard to the rotor position. Such an asymmetry in air gap and resulting flux linkage distribution produces an asymmetric torque such that there results a non-zero torque for all rotor positions when sum of the both phase contribution is considered for the air gap torque. This feature uniquely enables starting and running of the machine in any direction from any rotor position.

The manner in which the slots are placed in the rotor pole and the shape and size of the rotor slots is determined by the starting torque requirements. It is also determined by the nature of the application. Regardless of the manner of the rotor slots placement and as long as they are not symmetric with respect to the center of the rotor pole is covered by this invention. In a two phase

machine, the arrangement of the rotor poles with slots can be very similar to that shown in Figure 18.

SIXTEENTH EMBODIMENT

Description

Fig. 20 illustrates a slotted rotor pole, having slots separated by lamination material, according to a sixteenth embodiment of the invention. As illustrated, the rotor slots have increasing air gap as seen from the left but are interspersed with rotor lamination material so that the slot is not one but many. This simplifies the fifteenth embodiment as it combines both kinds of slots in one part of the rotor pole itself. The way slotting is done is primarily decided by a number of factors such as application, starting torque and acoustic noise, etc. In a two phase machine, the arrangement of the rotor poles with slots can be very similar to that shown in Fig. 18.

Some of the features provided by the sixth through sixteenth embodiments include:

1. The slotting of the rotor increases or decreases the effective air gap in clockwise (CW) or counter clockwise (CCW) depending on the rotor slot axis being on the right or left shifted, respectively.

2. Item (1) provides the preferential torque generation in one or other direction with no zero torque instances in its rotor position for both the phases combined.

3. Starting in CW direction when the phase corresponding to that direction of rotation has zero torque: When the torque for one phase is negative and the other phase is zero, the machine phase with the negative torque is excited, so that the machine runs in the CCW direction initially and its direction can be reversed to CW direction by the other phase excitation as the rotor pole moves

by 30 degrees for a 4 pole stator and 6 rotor poles. Therefore, the machine can only cater to applications that can tolerate this initial running in any of the two directions to start with. But it runs eventually in the desired direction is to be noted. Many appliance applications can stand this small inconvenience for a larger gain in the form of savings in machine and power converter cost mainly arising from smaller number of phases.

4. This machine is inherently capable of four quadrant operation with a two phase power converter that had been the subject of at least 7 disclosures incorporated herein. Such a four quadrant operation capability places this machine at an advantage in multiple applications that are emerging in appliances.

5. Many other converter configurations besides those described herein may also be used. But none of them provide the advantages of low cost, high reliability and low part count as those described herein.

6. The rotor and stator have symmetric structures and, therefore, no mechanical unbalance is foreseen and hence no radial pull forces are expected in this machine. That leads to a longer bearing life and a quiet machine operation also.

7. The same machine can also be run as a single phase SRM with one phase serving as a main phase and the other serving as an auxiliary phase similar to that of the single phase induction motor.

8. Slotting of the rotor removes iron and hence lowers the rotor weight. This has the beneficial effects of lower inertia and higher acceleration capability, both desirable qualities in aerospace and defense applications and also in machine tool servo and spindle motor drives.

9. The manner in which the slots in adjacent rotor poles are placed determines the asymmetric or symmetric torque in phases and

their shape with regard to rotor position. For example, one with as shown in Fig. 15 generates a constant or flat torque during conduction.

10. The slotting can be applied not only to one and two phase machines but also to multiphase machines to shape their torque, reduce acoustic noise and to increase power density.

11. Also the rotor slots can be filled with permanent magnets to create a new class of interior permanent magnet machines that are ideal for high speed operation and to produce a torque by augmenting the reluctance torque with the synchronous torque.

12. Rotor slots can also be used to house permanent magnets to serve as sensors in measuring the rotor position required in the control. Thus the rotor slots serve two different functions, i.e., both torque shaping and sensor housing.

Figs. 21 and 22 provide alternative slotting structures that may be applied to the twelfth through sixteenth embodiments.

SEVENTEENTH EMBODIMENT

Description

The seventeenth embodiment of the invention concerns Stator and Rotor Laminations for SRMs. This embodiment is described below.

Related art technology is based on the fact that the stator poles are being placed on the center or corners without due regard to acoustic noise considerations and without a theoretical basis. The present embodiment of the invention provides a systematic method of choosing the corner poles in the square or center placed poles with due consideration for manufacturing without wedges to hold the stator coils and with wire wraps welded in to the stator laminations thus providing a mechanically robust and vibration minimized machine. This embodiment provides a significant change

in acoustic noise, vibrations, and thermal robustness and is useful in all possible applications using SRMs.

This embodiment of the invention attempts to solve some of the salient problems in the manufacture and in acoustic noise control problem in the switched reluctance and permanent magnet brushless dc machines (PMBDCM), particularly in two phase machines. The manufacturing innovation can be used in SRMs and PMBDCMs that have more than one phase. The two innovations are:

1. Measures in design to reduce acoustic noise, and
2. Measures in design to secure the stator windings that are concentric.

The challenge in reducing the acoustic noise in SRMs is addressed by many ways. They are in electronic switching (refer to Pollock and others) and or in the design of the machine with a large back iron thickness and other measures detailed in R. Krishnan, Switched Reluctance Motor Drives, CRC Press, June 2001. While these measures have yielded a machine that has an acoustic noise comparable to other kinds of machines, there are still innovations possible to reduce the acoustic noise in the machine. It is well known that predominantly radial (also known as normal) forces generate acoustic noise in electrical machines. Therefore, one way to reduce the acoustic noise is to minimize the radial forces. That can be accomplished at the machine design stage. But the ratio between the radial and tangential forces can only be minimized to a level beyond which the useful tangential force is penalized. Then other measures are called for. One way to reduce the acoustic noise is to have the minimized radial forces that are unavoidable in a SRM due to manufacturing tolerances and then to reduce its impact on the stator structure by means of increasing the iron path in the stator pole and its back iron. That can be implemented in a two phase SRM (or for that matter in a concentric wound PMBDCM also) as explained in the following.

Given a four pole two phase SRM, the poles can be located in the corners of the stator square laminations, shown in Fig. 23. Compared to the location of the stator poles in the middle of the square sides, this instantaneously increases the length of the stator pole and its back iron
considerably as shown in the Fig. 24. This increases the stator pole length from $(r-r_{is})$ to $(1.414r-r_{is})$ where r is the radius of the inner circle in the square stator lamination and r_{is} is
the inner radius of the stator lamination at the stator pole tips as shown in Fig. 25a.

Defining k as the ratio between r_{is} and r and in terms of this normalized unit, the increase in the stator pole length can be derived as $f(k)=(1.44-k)/(1-k)$, and it is plotted against k in Fig. 25b. This shows that the pole length effectively increases by a factor of 45 to 75% or so with this strategy. Note that this does not decrease the radial forces but provides an enhanced acoustic impedance to minimize the stator vibrations that are the cause of the acoustic noise in the machine. Note that the hole for bolts in the stator does not interfere with the flux paths in the stator whereas in a circular stator lamination it impacts detrimentally if additional stator back-iron thickness is not built into the design.

Note in Fig. 23 the new and inventive method of securing the stator windings. It is based on the fact that steel wire wraps are inserted in to the holes punched in the stator laminations and run over the stator windings and welded on the outer part of the windings. Or alternately the wire wraps can be welded in to one side of the stator lamination hole and then wrapped around the windings and pulled with a tension, then inserted in the other side of the hole in the stator laminations and welded finally to keep the stator windings in place. These arrangements completely eliminate the need for wedges as used in related art devices. It is shown in Figure 23 and the steel wrap is shown in Fig. 26.

Instead of a steel or wire wrap, an industrial grade twine, or nylon twine can be used to tie the windings to the stator iron. In order to facilitate the securing process, two holes can be used for securing the stator winding on one side instead of only one hole. The advantage of this method is that it is much easier than the other method with wire wrap as the twines can be flexible, and no welding is required as in the other implementation of this embodiment.

The related art method of wedges have easier installation when the teeth have over an overhand or lips or pole shoes like structures so that there have a support for the wedges to stay. The disadvantage is that the winding insertion becomes a problem unless it is machine wound and inserted as a single operation thus leading to higher manufacturing costs.

Note that SRM stator poles do not have overhangs or lips or pole shoes for the primary reasons of low cost manufacture in punching the lamination and also for easier installation of coils without too many machine based manufacturing operations. Therefore, a newer method of coil securing is necessary for SRM production. The disclosed method is simpler to implement, much more stronger, and uses the stator lamination core for foothold without affecting the main flux paths and without interfering with the regular flux paths. As seen from Fig. 23, the iron that is taken off for the foothold holes to hold the wire wraps does not affect the area required for flux flow and, therefore, does not increase the flux density in the stator iron. Such a method, without affecting the machine electro magnetically, i.e., without interfering with the flux flow, or increasing iron losses or increasing the weight of the iron (actually decreases the iron weight by the removal of the iron for the holes) while simultaneously serving a useful mechanical purpose of providing footholds for wire wraps and securing mechanically the coils to the

stator iron and stator poles, is new and novel. It is not obvious since with prior lamination style shown in Fig. 24, there is no place for such holes and if holes are punched then they are at the expense of distorting the flux flow, increased flux density in the stator iron, and higher core losses. Therefore, the square frame laminations with stator poles and coils in the corners of the square laminations provide such an ideal and a natural arrangement for the foothold holes in the laminations.

This embodiment of the invention can be embodied also for stator poles in the middle of the square or circular laminations as shown in Fig. 27. Note that by beveling the stator pole base flat instead of an arc base as in related art stator laminations, enough space for stator holes to secure the coils is obtained. The same space is also non-interfering with the main flux path and does not lead to higher flux density and higher core losses. Such an arrangement is an extension of our method of securing the stator coils to the stator poles but as well as to the stator back iron. The singular advantages of this method are that the stator coils are in contact with both the stator's back iron and stator pole sides resulting in maximum contact area for heat dissipation and higher thermal robustness of the machine. This invariably increases the power density of the machine, as its coil temperature is lower for the same power output of the machine in comparison to a related art SRM whose coils have only physical contact with sides of the stator poles and not with the stator back iron resulting in higher coil temperature because of poor thermal conduction paths.

Some of the features provided by this embodiment include:

1. A two phase SRM or PMBDCM with four poles located in the corner of the square stator laminations to reduce the acoustic noise.

2. The said machines with these corner poles provide enhanced acoustic impedance to the stator vibrations to radial

forces induced by the magnetic forces and amplified by the manufacturing tolerances.

3. Such corner poles do not interfere with the mechanical securing of the stator laminations with through bolts and do not interfere with the magnetic paths and hence the force or flux production in the machines.

4. This embodiment of the invention may be applicable and limited to the four-pole, two-phase SRMs and PMBDCMs.

5. Such machines also have provisions to secure the stator windings without wedges.

6. Such means to secure the windings do not involve magnetic flux path interferences (as demonstrated).

7. The means to secure the windings are extendable to multiphase concentrically wound stator windings of SRM and PMBDCM and not limited to two-phase machines only.

8. The wraps to tie the windings in place can be any nonmagnetic materials but not electrically conducting.

9. The wraps to tie the windings can also be spot-welded in the case of wires or in the case of the plastic wraps can be tied with least manufacturing operations. The tension in the wire wraps can be adjusted with their lengths.

10. The method of securing the stator coils to the stator poles also comes into contact with stator back iron in another embodiment of the invention leading to lower temperature rise in the stator coils during machine operation which is a very good advantage for longevity of machine coils and also higher reliability of the machine operation since the coil failure either due to its breakdown of insulation is much less with this embodiment.

11. The stator windings can be secured with industrial grade polymer twine or nylon grade twine to provide simplicity in

production process and use of more than one hole for securing the stator windings with the said twines.

EIGHTEENTH EMBODIMENT

Description

The eighteenth embodiment of the invention is a Two Phase Permanent Magnet Brushless DC Machine (PMBDCM) for Operation with a Single or Two Switch Power Converter. This embodiment is described below.

Fig. 28 illustrates one implementation of this embodiment having a two-phase PMBDCM with four rotor permanent magnets and four salient poles with concentric windings. The coils in the stator poles are former wound for easier manufacturability. Diametrically opposite coils are connected in series or in parallel and each of such connections present a winding called phase winding. Therefore, this machine configuration has only two-phase windings. Note that they are spatially shifted from each other by 90 mechanical degrees (or 180 electrical degrees) and that need not be the case. In order to optimize the torque generation of the machine, say with a single switch power converter topology, the spatial phase shift between the stator phase windings may be other than 90 degrees as discussed in another of the disclosed embodiments. The coils are secured with wire wraps or twines or nylon threads for holding them in place as discussed in a previous invention.

Some advantages and features of this embodiment are:

1. It may be viewed as a single-phase machine with two windings displaced 180 electrical degrees apart but it is used as a two-phase PMBDCM for variable speed operation and control.

2. The flux paths have symmetry in each quadrant (i.e., 90 mechanical degrees) and, therefore, there will be minimum net

radial forces resulting in very stator acceleration and hence in low acoustic noise of the machine.

3. The machine, unlike a traditional 2-phase machine, has 180 degrees displacement between its induced emfs and, therefore, it is ideal to operate in half-wave control mode. That is, only when the induced emfs are positive, a positive current is injected in to the respective windings. When that is done, the torque is uniform and does not have zero interval for 1/4th of the electrical cycle as in the case of the traditional 2 phase machine. See Figs. 29a and 29b for an explanation of this fact. Note that the currents are injected in to the windings when the emfs are positive, and, therefore, producing positive air gap power, P_{ag}, and hence positive torque. It can be observed from Fig. 29a that the air gap power is constant over the electrical cycle of 2-phase part of the electrical cycle. This reflects in the torque in high ripples and, hence, noise in the machine. Note that both the machines produce on an average the same amount of air gap power and torque.

4. Under-utilization of the machine windings happens as the windings are utilized only for 50% of the time with half-wave operation. Note that such a disadvantage does not exist in the full-wave operation (i.e., when the windings are injected with bi-directional currents).

5. The output power of the machine does not suffer very much. The rms current in the winding is $0.707I_p$ and for the same amount of copper losses, i.e., $2I^2{}_pR$, the stator current can be increased by 1.414 times the peak current. Therefore, the current in the winding can be increased by 41.4% resulting in the same amount of copper losses as in the case of a related art two phase PMBDCM. That increases the power output to $1.414E_pI_p$ as compared to $2E_pI_p$.

6. Interesting comparison to full-wave inverter fed three phase PMBDCM: Emf per phase, E_{p3} and that is equal to half the source voltage, V_s. The net power output is $2E_{p3}I_p$. In terms of the 2 phase machine, $E_p = V_s$. Therefore, $P_{ag3}= 2E_{p3}I_p=2*V_s/2*I_p=V_s*I_p$. For this embodiment of the invention of the two-phase machine, $P_{ag}=1.414E_pI_p = 1.414V_sI_p$. That is a huge improvement for this embodiment of the invention and hence, it is superior to related art three phase PMBDCMs.

7. Assume that the induced waveform is 120 deg. flat (i.e., trapezoidal) on each half cycle in the present embodiment of the invention as in the related art PMBDCM. Even for such a case, the present embodiment produces a power of $1.1547E_pI_p = 1.1547V_sI_p$ which is 15.47% higher than the related art three-phase PMBDCM's output (with a current of $1.732I_p$ in the present embodiment). Therefore, the present embodiment of the invention has higher power output but comes with a disadvantage of higher number of turns since the induced emfs are high (double that of the 3 phase machine). Or if the number of turns is not increased, then the present embodiment of the invention can operate at twice the speed of the three-phase PMBDCM for the same torque output resulting in higher power at the highest speed.

8. Let the number of turns in this embodiment of the invention is equal to 1.5 times the number of turns in a 3-phase PMBDCM. For equal copper fill factor and fill volume, the resistance of the stator winding in this embodiment of the invention is equal to 9/4 times the resistance of the 3-phase machine resistance. Therefore, the current in our machine is adjusted for equal copper losses as $1.1547I_p$ where I_p is the peak stator current in 3-phase machine. Therefore, the air gap power for the present embodiment of the invention is $1.1547E_pI_p$. This is assuming that the conduction is only 120 degrees in the positive half of the cycles.

9. For the same condition as in (8) but for full-wave operation with 120 degrees conduction in each half cycle, the power output is $1.6328E_pI_p$ and the current is modified to be $0.8164I_p$ for constant copper losses in the present embodiment of the invention. This machine has decreased output because its current is decreased resulting in equal torque per unit current to that of the 3-phase machine. The power and torque de-ratings are 18.35% compared to the related art 3-phase machine.

10. Note that the dc source is not fully utilized for the present embodiment of the invention as there is a reserve of more than $0.5E_p$ for cases (8) and (9). That means, the present embodiment of the invention has a larger constant torque region, at least by 33% of speed region.

11. Even assuming at the worst there is a de-rating of the motor, the motor drive as a whole has minimum number of components for its realization. That is the unique aspect of this motor drive.

The principle of operation for the machine is self explanatory from Figs. 2a and 2b. The operational modes may be summarized as follows:

1. Forward Motoring (FM): Phase sequence is ab. Inject positive currents when the induced emfs are positive for 180 degrees in each phase. The torque is positive (CW) and rotation is CW.

2. Forward Regeneration (FR): The speed is CW and it is required to brake the machine to zero speed in a controlled manner. Inject a controlled current in to phases when their induced emfs are negative resulting in regeneration and negative torque that will decelerate the machine.

3. Reverse Motoring (RM): In order to run the machine in CCW direction, change the phase sequence from ab to ba and inject positive currents into windings when their induced emfs are

positive resulting in CCW torque and spinning of rotor in CCW direction.

4. Reverse Regeneration (RR): To brake the machine in a controlled way when it is running in CCW direction, apply positive currents when the induced emfs in the windings are negative resulting in negative or regenerative torque and hence in the deceleration of the rotor and its load.

Realization of the controller and power electronic converter is obtained as follows. Any of our single or two switch power converter topologies and a simple controller will be able to run the disclosed motor with variable speed in all four-quadrants as given in the principle of operation. Descriptions of the power converters are provided or referenced herein. The controller can be any standard text book controller and for only two phases instead of three phases and described in R. Krishnan, "Electric Motor Drives", Prentice Hall, Feb 2001 (book).

The machine may be self-starting. From Figs. 29a and 29b, it can be seen that there are two detente or zero torque positions, i.e., at zero crossings of the induced emfs of both phases. Note that the induced emfs of both phases go through the detente at the same positions. If the rotor happens to be in that position, then starting becomes impossible. Moreover, in this invention, the chances of the starting position will be at those detente points as the rotor magnets will tend to align with the stator teeth (or poles). Therefore, in order to facilitate self-starting, it is imperative that the phase windings are displaced from each other not by 180 electrical degrees (90 mechanical degrees in the illustrated case) but by less than or greater than 180 electrical degrees. This will make the detente positions to be different for the 2 phases ensuring that a non-zero torque is available at any given from the combined operation of the two phases.

Phase shifting to avoid zero torque instances: (i) One way to obtain the phase shift of the phases is by shifting one of the phases stator teeth or poles by the desired angle. (ii) Or alternately, the alternate rotor magnets pair can be shifted to the desired angle of anything other than 90 mechanical degrees in the illustrated case of Fig. 28. Easier would be shifting the alternate rotor permanent magnet poles.

Starting under this condition: Various instances present themselves for starting. They are very similar and identical to starting and running as disclosed herein (see the Two Phase Permanent Magnet Brushless Dc Machine (PMBDCM) with Single Switch Power Converter Drive System embodiment). Therefore, they are not elaborated here.

This embodiment of the invention is useful in low cost variable speed applications, such as for appliances and cooling fans, etc. Some of the features provided by this embodiment include:

1. A two phase machine with less than or greater than 90 electrical degrees phase shift between the two phases.

2. The phase shift is closer to 180 electrical degrees and differs by only a small angle of 10 to 15 degrees from 180 degrees in this embodiment of the invention.

3. Such an embodiment of the invention with two phases and said phase shifts between the two phases is ideal for operation with single and two switch converter topologies for variable speed operation of the motor drive.

4. The operation of the invented machine in unidirectional current injection with half wave converters is not restrictive of this embodiment of the invention and the operation can be extended to full wave operation with alternating current injection in to the windings with appropriate converters. As such the machine for half- and full-wave operations are disclosed.

5. The said machine's phase shift is determined by the load torque requirements at starting and therefore, the phase shift is variable and is not fixed for all designs.

6. The machine with four stator teeth and four rotor permanent magnets on its rotor is the most compact embodiment of the invention.

7. The machine other than four rotor permanent magnets and multiples of four stator teeth or multiples of four of the rotor permanent magnet poles and also of the stator teeth are other possible embodiments of the invention and all of them with or without phase shift of other than 180 electrical degrees are disclosed.

8. Desired phase shift between two phases is embodied by the stator poles or teeth shift of one pair as against the other or also embodied by the alternate rotor permanent magnets shift as against the other pair of the diametrically opposite rotor permanent magnets. Such a phase shift generation in a two-phase PMBDCM is desirable.

9. An unequal number of turns in the two phase windings is of use in particular applications to optimize the converter operation such as in single switch converter based variable speed motor drive.

10. The phase shift introduced in this embodiment of the invention is to have self-starting of the machine in both directions of rotation and such self-starting with the means of a power converter.

11. Operation of the machine in all four-quadrants.

NINETEENTH EMBODIMENT

Description

The nineteenth embodiment of the invention is a Two Phase Permanent Magnet Brushless DC Machine (PMBDCM) with Single Switch Power Converter Drive System. This embodiment is described below.

Related art PMBDCM technologies are mainly based on:

1. a full wave three phase PMBDCM drive with six or four controllable switches,

2. a half wave three phase PMBDCM drive with four controllable switches, and

3. a two phase PMBDCM drive with four controllable switches.

Given these technologies, it is difficult to reduce the cost of the overall PMBDCM drive system to compete with a single switch PM brush dc machines/universal machines or constant speed three or two phase induction motors. This is because the cost of the power converter and its controller are expensive due to higher number of controllable switches used in these converters and their attendant requirements for additional power supplies, gate drive circuits, heat sink area and volume and consequent overall packaging size and component and shipping costs. The nineteenth through twenty-first embodiments of the invention overcomes all of these disadvantages and still provides a four-quadrant operation with only one controllable switch for a brushless machine, hitherto unheard of in the literature.

Revolutionary upheaval in the field changes the current thinking on ac brushless drives, which is wedded to six controllable switch based inverter drives and having a three phase machine. Both of these paradigms are challenged in this embodiment of the invention, which provides a solution with the least expensive PMBDCM, least expensive power converter with one single controllable switch only, and the most simplest controller to provide an overall four-quadrant variable speed drive with the lowest cost. Because of these factors, this embodiment challenges the primacy of universal motors in all low cost applications and

provides for the same cost a four-quadrant variable speed drive with a PM brushless dc machine. This has never been achieved in this field and by replacing the fixed speed universal motors with this invention of a 2 phase PMBDCM drive system, higher efficiencies, higher reliability, lower hazardous operation, variable speed operation in four-quadrants and doing with commutators and brushes are all achieved.

The nineteenth embodiment is a permanent magnet brushless dc motor (PMBDCM) drive with two phase windings and with a spatial distribution of 90 electrical degrees or higher wound on salient stator poles. Such a machine is combined with a single switch per phase converter, such as is disclosed in the twentieth embodiment, to devise a variable speed operation in clockwise and counter clockwise directions with regenerative braking in both directions of rotation, known in literature as four-quadrant variable speed operation. A controller that can run this machine with the converter is disclosed, in the twenty-first embodiment, for the four-quadrant operation. Such a combination of the machine, the converter, and the controller results in the lowest cost and the most compact (in volume and weight) variable speed PMBDCM drive. Such a low cost PMBDCM drive has not been in practice in industrial applications and such a motor drive has not been previously disclosed in the art.

This embodiment concerns a two phase PMBDCM with a spatial distribution of windings of 90 electrical degrees or higher with salient poles in the stator and concentric windings around the stator salient poles. The rotor has two magnets placed on laminations (known as surface mount type) or that may be grooved into the laminations partially (surface mount type) or fully (inset type) or buried (interior or buried type) inside the laminations to obtain a rotor. The arc of the magnets is less than 180 electrical degrees so as to minimize the leakage flux between the two magnets.

Even though we consider two rotor permanent magnets, there is no restriction to the even number of permanent magnets one could have on the rotors. The machine has stator laminations with 4 teeth (for two permanent magnets on the rotor) or multiples of 4 teeth that could be termed as salient poles (for multiples of two permanent magnets on the rotor) and very similar to that of a switched reluctance machine. Consider for the time being a four teeth stator lamination with the slot width being much higher (say, at least by a factor of 1.33 and above) than that of the teeth. Let concentrically wound coils be placed around each tooth. The coils from the diametrically opposite stator teeth (in the case of a machine two permanent magnets on the rotor) and, in general, windings that are displaced by 180 electrical degrees are connected in series to form one phase winding. Therefore, from this description it is deduced that two phase windings are obtained from a four teeth machine with a pair of permanent magnets on the rotor. Such a machine is shown in Fig. 30. Note that the spatial shift between the two phases need not be exactly 90 electrical degrees and it can be much higher and such a machine with a spatial shift of more than 90 electrical degrees is shown in Fig. 31.

Fig. 32 illustrates a winding diagram for the two phase PMBDCM of the nineteenth embodiment. Coils 1 and 2 are placed on teeth 1 and 3 and coils 3 and 4 are placed on teeth 2 and 4. Coil 1 has terminals A1 and a1, coil 2 has terminals a2 and A2, coil 3 has terminals B1 and b1 and coil 4 has terminals b2 and B2. The first terminal indicates the beginning of the coil and the second terminal indicates the ending of the coil. Coils 1 and 2 are connected in series and likewise coils 3 and 4 are connected in series. Winding with terminals A1 and A2 gives phase A and winding with terminals B1 and B2 gives phase B.

Fig. 33 illustrates the flux linkages and induced emf waveforms of the two phase PMBDCM, having the spacial shift of 90

electrical degrees, according to the nineteenth embodiment of the invention. The principle of operation of the two phase PMBDCM is very similar to that of the three phase PMBDCM. But this embodiment of the invention does not use full-wave operation (i.e., alternating currents in the machine windings) but only uses half-wave operation, i.e., it injects only unidirectional current in machine phases. In order to understand the controller that is disclosed in the twenty-first embodiment, it is imperative to have an understanding of the induced emfs in these phases when the rotor spins and particularly their spatial and hence time relationship to each other.

The induced emfs for this two phase PMBDCM are shown in Fig. 33. The basis for that is elementary and is derived from time derivative of the flux linkages of the stator phases. This basis can be found in this disclosure or in the literature referenced herein.

When currents of the same polarity as that of their induced emfs are injected in the machine phases, a unidirectional torque is generated in the machine that is smooth for an ideal machine. That means alternating current is required for the machine phases and that requires at the minimum 4 controllable switches in the power converter. But then the dc voltage applied to the windings is half its nominal value thus resulting in greater derating of the dc link voltage and hence in the higher current rating of the machine phases and higher rating of the controllable switches leading to higher cost of the variable speed drive system. Such a solution is known by the applicant and not widely used.

Compared to related art machines, the disclosed machine has the following advantages.

1. Simpler stator laminations and, hence, their simpler punching requirements.

2. Concentric coils that are easier to wind (former wound coils) compared to related art distributed coils that usually are machine or hand wound and very complex in machine manufacturing operations resulting in higher cost.

3. No pole shoes or wider front end for the teeth than at its back end thereby eliminating the mandatory winding by the machine for the coils.

4. The number of turns in these coils need not be the same as in the related art machine as the present invention does not use both the windings for machine torque production equally.

5. The spatial shift between the phases need not be exactly 90 electrical degrees as in the related art machine. In fact, a spatial shift of other than 90 electrical degrees is very beneficial for the disclosed variable speed drive operation and is proven in the controller section. Therefore, precision machining to guarantee perfect 90 space shift between the machine phases is not required and the more the error, the better is for the disclosed invention. Unlike related art PMBDCMs, the machining tolerance is high in this machine.

6. The mutual inductance between the phase windings is almost nonexistent in the disclosed machine and hence the machine can be highly fault tolerant as the fault in one winding does not affect the operation of the other. This is a great advantage in high reliability applications. This feature makes the machine very similar to the switched reluctance machines in fault tolerance.

7. The machine can have stator laminations that are square and with teeth centered around its corners (shown in Fig. 34) so that they can have multiple advantages outlined in the following:

- Rigid base support for the stator teeth and hence very small acceleration due to the normal forces resulting in lowest acoustic noise generation and, hence, resulting in the quietest machine.

- A very simple construction for mechanical assembly with through bolts in the corners without affecting the flux path.

- A larger thermal dissipation outer surface for better cooling of the machine.

The 0 (corresponding to 12 o'clock position), 90, 180, and 270 degree positions on the stator are available for sensor mounting as they lend themselves for sensor mounting to detect the rotor magnet position for control. Note that it does not require extra magnet wheel on the rotor for position sensing as in a related art PMBDCM. This results in a big saving in cost in many applications. Again the sensor need not be an optical sensor or a Hall effect sensor as it can be a small coil around a small tooth at these stator angles of 0, 90, 180 and 270 degrees. Note that they do not provide starting position and that is ascertained by other means.

8. The stator windings can be held in place in ways similar to those described herein for other embodiments of the invention and, therefore, the teeth do not have a need for an overhang or pole shoes.

This embodiment of the invention solves the problem of high cost, and low compactness associated with current motor drives using PMBDCM drives. It provides a four-quadrant variable speed operation of a PMBDCM drive with minimum electro magnetics, electronics and control thus making it an ideal candidate for low cost applications in appliances and automotive applications. Some of the features provided by this embodiment include:

1. Two phase PMBDCM with spatial shift between two phases greater than 90 degrees (or even equal to 90) degrees for maximization of torque generation with a single power switch converter topology.

2. Two phase PMBDCM with four slots for two permanent magnets on the rotor or multiples of four slots for multiples of two permanent magnets on the rotor.

3. The slots with the width being equal throughout its height and without pole shoes.

4. The number of turns in the phase windings and their wire sizes are different and can vary significantly from each other.

5. The mutual inductance between the windings is almost nonexistent in the invention as it does have only concentric windings on each tooth.

6. The windings are secured to the stator back iron by unique straps.

7. The machine stator, in the case of four stator slots, has all the teeth in the corners of the square laminations resulting in high thermal stability and lowest acoustic noise.

8. The invention is fundamental since the functioning hardly changes regardless of the way permanent magnets are mounted on the rotor, such as surface mount, inset or interior permanent magnet rotors.

TWENTIETH EMBODIMENT

Description

Fig. 35 illustrates a single power switch converter for a two phase PMBDCM according to a twentieth embodiment of the invention. This power converter has one controllable power switch for operating and energizing both machine phases. Note that phase A is auxiliary used primarily to recover the snubber's (Cs) , and phase B's energy during turnoff and, therefore, it has much less rms current rating than that of phase B. Phase B is the main phase of the machine contributing to motive power to the machine and hence that phase is the most actively controlled with the controllable switch T1. Through active control of phase A, we are able to exercise a significant amount of control on Phase B may be discerned. For example, the turn off instant of T1 depending upon whether phase A has maximum positive or negative induced emf

determines the duration of phase B's current conduction. The operation of the converter is very simple and elegant. When motive power from phase B has to be extracted, switch T1 is turned and by pulse width modulating its gate control, the current in phase B is regulated. When phase B is unable to provide any more motive power of particular polarity, then current in it is extinguished by turning off switch T1. On turn off of T1, note that the energy stored in the inductance of phase B is transferred to the snubber capacitor, Cs, by charging it above and beyond the dc source voltage. That circulates a current in phase A through the dc source voltage resulting in positive or negative torque in the machine, and with some additional exchange of energy between the snubber and dc source.

The polarity of the windings of phase A and phase B are positive on the top and their connection forms the common terminal for the machine for connection to the power converter. This particular arrangement of polarity for phases A and B provides the maximum productive torque region for the disclosed machine can be proved from first principles. The fact that different polarity arrangement may be used is enclosed by this disclosure and invention.

This embodiment of the invention solves the problem of high cost, and low compactness associated with current motor drives using PMBDCM drives. It provides a four-quadrant variable speed operation of a PMBDCM drive with minimum electro magnetics, electronics and control thus making it an ideal candidate for low cost applications in appliances and automotive applications. The disclosed power converter has many unique advantages for driving the two phase PMBDCM. Some of these advantages are the following:

1. This is the only power converter topology with one controllable switch and one diode to control a two phase PMBDCM.

2. By using one controllable switch and one diode, the power converter is optimized both in terms of its weight, volume and cost as like none other.

3. The emitter of the controllable switch is tied to the negative rail. By making the negative rail the common for control circuits, isolation requirements for gate drive is eliminated. It results in a saving of an isolated power supply, space required for mounting it and cost associated with all of these.

4. Current control is accomplished with one resistive sensor in series with the emitter of the controllable switch thereby eliminating the need for isolated Hall current sensor resulting in a considerable saving in the feedback sensor cost. The current can be controlled in a novel manner as follows. The voltage across the sensing resistor, Rs, provides a measure of the current. When switch T1 is turned off, the current in phase B is unknown. Therefore, a very elegant method is disclosed here. Every switch cycle, T1 is turned off and the current is measured through the sensing resistor, R_s, after a sampling instant of 5 or 10 us. The sampling instant can be as small or more than the example given and it does not affect the basic nature of the invention being described here. Based on this current and reference current, the duty cycle for the pulse width modulator is determined. That way, the current during turn off is not required for control. This strategy, therefore, enables current control with one sensing resistor that is in series with T1's emitter and overcomes the need for isolation in control circuits. This is novel and is part of the invention for control circuit also. This embodiment of the invention uses a novel way of current control.

5. The zero crossing of the induced emf for phase B is determined with a resistor divided network across switch T1 consisting of R_{1T} and R_{2T} and a resistive divider across the dc source consisting of resistors R_{1s} and R_{2s}. A sample of the device

voltage, v_T (voltage across R_{1T}, reflecting the sum of the source and machine phase B's induced emf) subtracted from the sample of dc source voltage, v_s (voltage across R_{1s} reflecting the source voltage) gives the phase B's induced emf. From this signal, the positive and negative zero crossings of the phase B's induced emf can be determined. Those signals, respectively, initiate the beginning and ending of the current injection in phase B. Such a way of finding the induced emf and hence its zero crossings for activation of transistor switch T1 is novel.

6. The power supply for the control circuit is derived form the dc link voltage through a resistive divider network (R_{p1} and R_{p2}), a capacitor, C_p, to store the energy and a zener diode, Z_p, to maintain the desired voltage for the control power supply. Note that the power supply voltage is referenced to the negative of the dc source. Since all the voltage and current signals are referenced to the same negative, there is no need for isolation for control signals and gating signals in this power converter arrangement. A huge savings in component costs associated with isolation requirement is achieved with this embodiment of the invention. The derivation of power supply for use with the two phase PMBDCM is a part of this embodiment.

7. For low power applications, note that a diode bridge rectifier to rectify the ac to dc voltages is not necessary. A single diode may be sufficient resulting in further savings. This aspect for cost reduction and compactness of the motor drive is a part of this embodiment of the invention.

8. There is no need for a separate snubber to protect the device T1 from high rate of change of voltage during its turn off as the capacitor, C_s, serves as the snubber.

9. Allowing bi-directional current flow in phase A results, on the average, in some positive torque generation. Addition of a diode in the path of phase A thus limiting its current to one

polarity may reduce the net torque output. Therefore, a circuit with diode in the path of phase A is part of another implementation of this embodiment of the invention.

10. Various variations of the single controllable power switch configurations as outlined herein are appropriate for the two phase PMBDCM drive and, therefore, may be used for the PMBDCM drives described herein.

11. The combination of the two phase PMBDCM and the single controllable power switch converter topology (or all our topologies) for the variable speed operation of the motor drive is unique.

12. The power circuit topology with its provisions for having current and voltage feedbacks and power supply generation together with a common reference to the power circuit and power switch to generate a low cost variable speed drive is unique.

13. The fact that there is no isolation requirement between control and power circuits in the disclosed power circuit is unique.

14. The particular polarities of winding phases A and B (with positive being common) and their connection to the positive rail of the dc source leading to the arrangement that lends to maximum torque is unique.

15. All other combinations of polarities of the phase windings to the converter circuit, though may be less optimal in terms of torque production, are covered by this embodiment of the invention.

TWENTY-FIRST EMBODIMENT

Description

The twenty-first embodiment of the invention relates to a controller to extract a four-quadrant operation of the two phase PMBDCM with the single controllable switch based power converter,

including starting from any rotor position. In order to derive the controller that is being disclosed here, consider the induced emfs with a spatial phase shift greater (or also less) than 90 degrees between the two phases of the machine shown in Fig. 36. For convenience, let the angle between the phase of phase B's voltage to lead the phase of the phase A's voltage by â (degrees). The polarities of the phase windings with the disclosed power converter topology shown in Fig. 35 is considered here for deriving the principle of operation of the motor drive and hence the controller.

When e_b is positive and as long it is positive, the switch T1 is turned on and current in phase B is maintained. Two situations arise here, one corresponding to regulation of current in phase B and two corresponding to commutation (turn off) of current in phase B altogether. They are further elaborated as follows.

1. When the switch is being turned off to regulate the current in phase B, then at that time, notice that the induced emf in phase A is negative. During turn off of the switch T1, the current in the switch is being diverted to the snubber capacitor thus charging it up resulting in an increase of its voltage, v_c. When the snubber capacitor's voltage is greater than that of the dc source, a current in phase A results. Notice, the current in phase A is negative as per the polarity of the winding and hence with a negative induced emf in that phase, a positive air gap power and hence positive torque is generated resulting in enhanced torque output of the machine.

2. When the switch T1 is being turned off to regulate the current in phase B, and if e_a is positive, then the energy recovered in the snubber capacitor is cycled to the dc source capacitor and during that instant, phase A is regenerating resulting in transfer of energy to the dc source also. Overall, the snubber capacitor's energy is periodically taken to the dc source or to the machine phase A and thereby, a dangerous build up

of energy and resulting high voltage across the snubber capacitor is avoided.

Consider the circulating current that may flow between windings from the following Table 1.

Table 1			
e_b	e_a	i_c	Comment
'+'	'+'	0	
'+'	'+'	>0	if $e_a > e_b$, arises for 30 or less
'+'	'–'	0	
'–'	'–'	0	$e_a = e_b$
'–'	'–'	>0	$e_b > e_a$,
'–'	'+'	>0	regenerative region and not very good but for a short time only

Symbol '+' means the induced voltage is positive, symbol '–' means induced voltage is negative and i_c is the circulating current between two machine phases. One solution to reduce the undesirable regenerative period is to increase (or can also be viewed as reducing) the spatial phase shift of the two phases. This is a unique aspect of the control.

Based on this understanding, the control strategy for operation in four-quadrants is derived as follows.

A. <u>Forward Motoring (Clockwise (CW) rotation and positive motoring torque, i.e., CW torque):</u>

1. At standstill, if B phase's flux density (B_b) is greater than zero, i.e., e_b>0, (and e_a>0), turn on switch T1 resulting in phase B current to rise from zero (i_b>0) and in a positive motoring torque and CW rotation of the rotor.

2. At standstill, if B_b < 0, (e_b <0) and e_a >0, then turn on T1 for a short interval of time such as few microseconds and turn

off to charge the snubber capacitor. That will retard the rotor in the counter clockwise direction and will thereby bring the rotor magnets to a position that is ideal for starting. Note that in this case, the rotor initially has to move in the direction opposite to that of the desired direction.

3. If e_b = '–', and e_a = '–', try step 2 and i_a = '–', resulting in positive motoring torque moving the rotor CW.

Similar steps such as given in 1,2 and 3 are applied for counter clockwise directional starting and it may involve initial movement of the rotor in the CW direction, say for a few degrees. Therefore, the applications that are insensitive to initial movement in either direction are highly suitable for the disclosed motor drive system. Note that overwhelming applications belong to this category. With steps 1 to 3, all conditions for forward motoring are guaranteed.

<u>B. Reverse Motoring (Counter CW rotation, CCW torque):</u>

Similar technique as in (A) but needs to make sure rotor is rotating in reverse direction from sensed or estimated signals.

<u>C. Forward Regeneration (CW direction of rotation, negative torque, i.e., CCW torque):</u>

When e_b <0, turn on T1 resulting in regeneration. Similar approach applies to the CCW direction of rotation.

<u>D. Reverse Regeneration (CCW direction of rotation, positive torque, i.e., CW torque):</u>

When e_b <0, turn on T1 resulting in regeneration.

With these tersely described steps (A) to (D), a four-quadrant drive with a single switch converter with two phase PMBDCM is achieved.

This embodiment of the invention solves the problem of high cost, and low compactness associated with current motor drives using PMBDCM drives. It provides a four-quadrant variable speed operation of a PMBDCM drive with minimum electro magnetics,

electronics and control thus making it an ideal candidate for low cost applications in appliances and automotive applications. The disclosed power converter has many unique advantages for driving the two phase PMBDCM. Some of these advantages are the following:

1. A two phase PMBDCM drive can be started from any rotor position with a single switch power converter. This embodiment alone guarantees the starting of the motor drive with a single switch power converter topology (SSPCT).

2. A two phase PMBDCM drive can be controlled in speed over its entire speed range with a single switch power converter. This embodiment alone makes possible a variable speed motor drive with a single switch power converter topology (SSPCT).

3. A two phase PMBDCM drive together with a single switch power converter topology can be operated in four-quadrants with the control strategy described herein. This makes it the only drive control strategy that can guarantee a four-quadrant operation with a single switch power converter topology (SSPCT).

4. The control strategy and its implementation steps disclosed in this embodiment can work with either sensor based or estimated rotor position.

5. The control strategy and its implementation steps disclosed in this embodiment can be extended to other single switch power converter topologies (SSPCTs).

6. With very few modifications, the disclosed strategy and implementation are applicable to the other controllable power switch topologies that have been disclosed herein. In those PMBDCM drives with two controllable power switch topologies, there is less probability of hesitation in starting.

7. The control strategy and its implementation steps disclosed in this invention can be easily extended to two phase switched reluctance motor drives with single switch power converter

topologies (SSPCTs) and also with two controllable switches based power converter topologies that have been disclosed herein.

Together, the nineteenth through twenty-first embodiments provide the following features.

1. A two phase PMBDCM with the said machine architecture, said single switch power converter topology and said controller in combination constitute a four-quadrant variable speed operation motor drive system.

2. Such a combination (i.e., of a two phase PMBDCM + single switch power converter topology + controller described earlier) as in (1) but with two controllable switch power converter topologies endows an independent control of the machine phase windings for high efficiency operation of the motor drive is also a four-quadrant variable speed motor drive.

3. The said combination (i.e., of a two phase PMBDCM + single or two switches power converter topology + controller described earlier) with the least number of isolated power supplies for logic and control.

4. The said combination with current and voltage sensors realized from resistive and capacitor elements requiring no isolation from the power common terminal thus saving both transducer cost and isolation cost.

5. The said combination with a unique current sensing and current control method.

6. The said combination of unique starting procedure of the machine and its operation over the wide speed range in four-quadrants.

7. The said combination of the two phase PMBDCM with concentric or form wound coils, salient stator poles, minimum number of stator poles (4 or multiples of 4).

8. The said combination of the two phase PMBDCM having rotor magnets placed in any manner such as surface mount, inset or interior.

9. The said combination of the two phase PMBDCM with stator poles on the corners of the square laminations to reduce acoustic noise.

10. The said combination of the wire wraps for holding the stator coils in place as given in my other disclosure for higher thermal robustness and easier manufacturability.

11. The said combination of the two phase PMBDCM with its stator salient poles having no lips or overhang or pole shoes for easier insertion of wound coils.

12. The said combination of the two phase PMBDCM drive having any one of the arrangements of the single switch power converter topologies.

13. The said combination of the two phase PMBDCM drive with control of one-quadrant or two-quadrant or four-quadrant in its variable speed operation.

14. The said combination of the two phase PMBDCM drive control with position sensors or without position sensors or with estimated position obtained through its voltage and or current, i.e., regardless of the position information is obtained for its operation.

15. The said combination of the two phase PMBDCM drive with its motor having equal or unequal number of turns of coil in its two phases for optimizing the torque output.

16. The said combination of the two phase PMBDCM drive with its motor having stator poles (or windings) shifted spatially by other than 90 degrees for optimization of torque output.

Figs. 37-49 illustrate additional features of the nineteenth through twenty-first embodiments of the invention.

Fig. 1

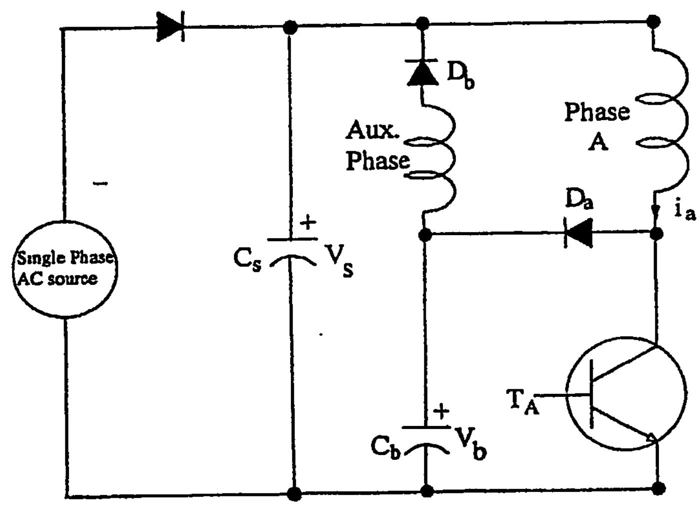


Fig. 2

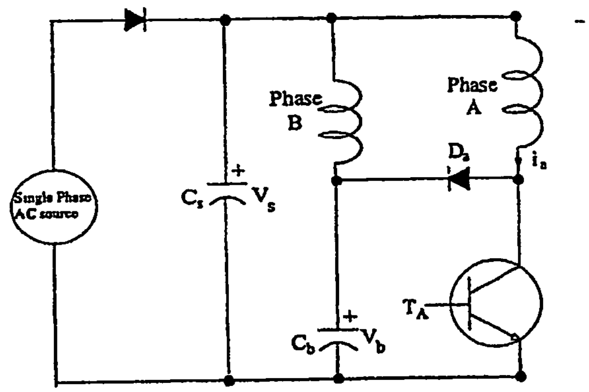


Fig. 3

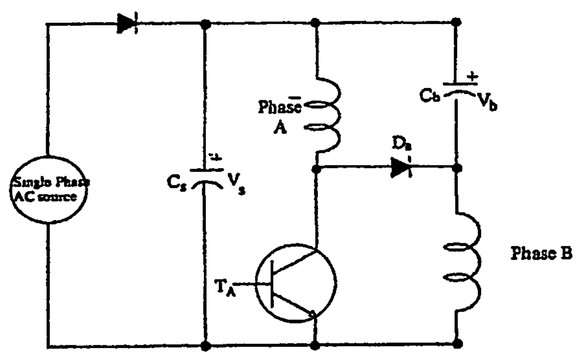


Fig. 4

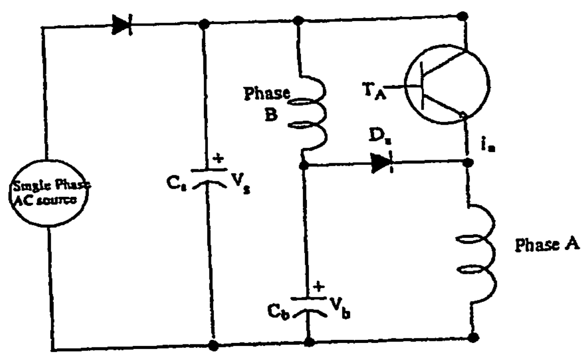


Fig. 5

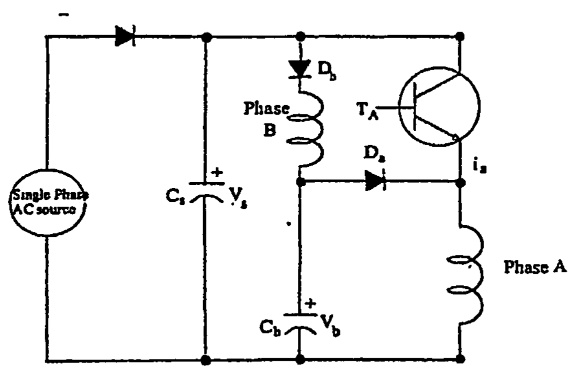


Fig. 6

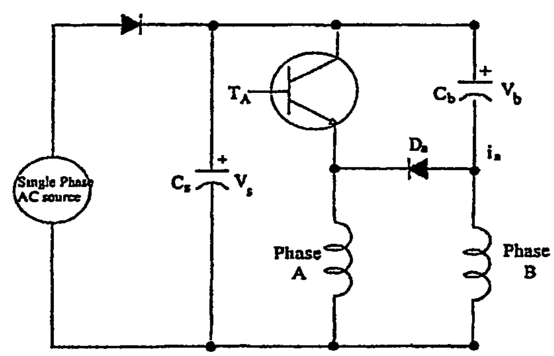


Fig. 7

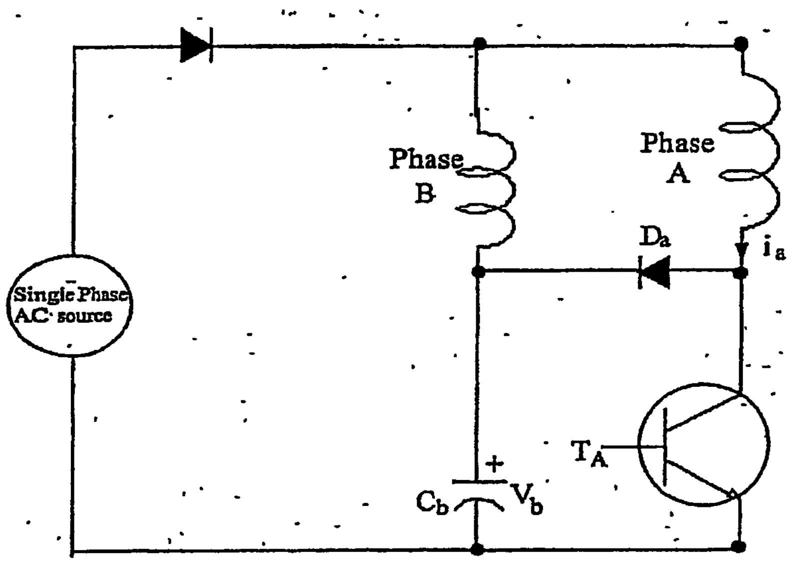


Fig. 8

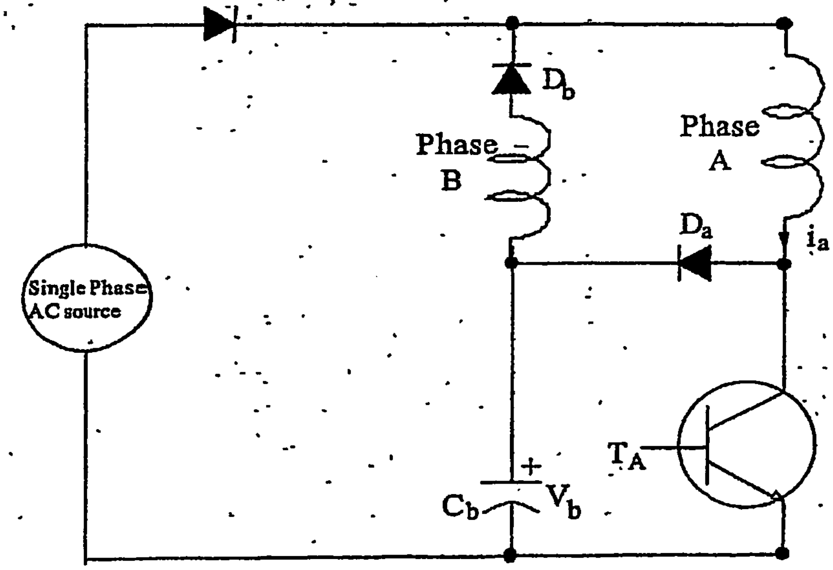


Fig. 9a

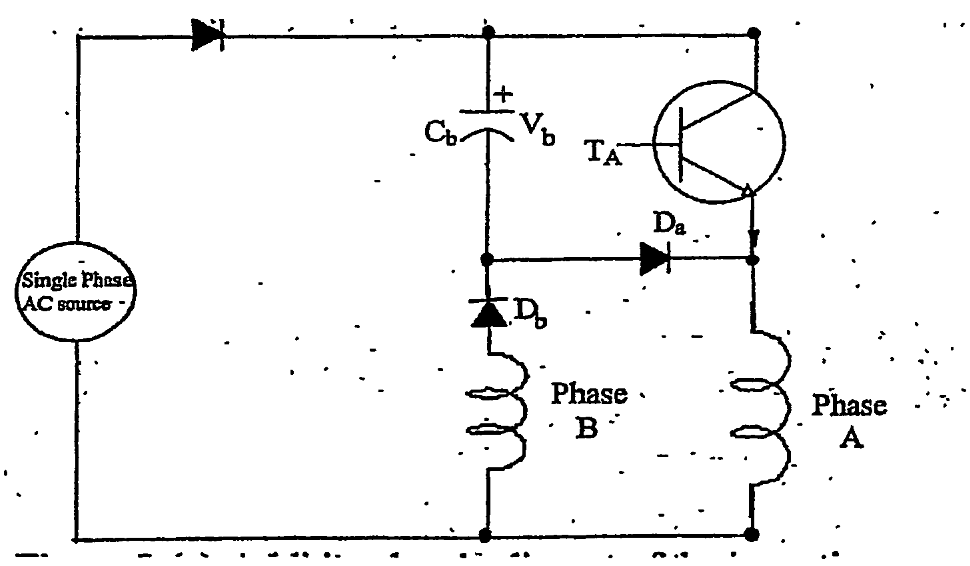


Fig. 9b

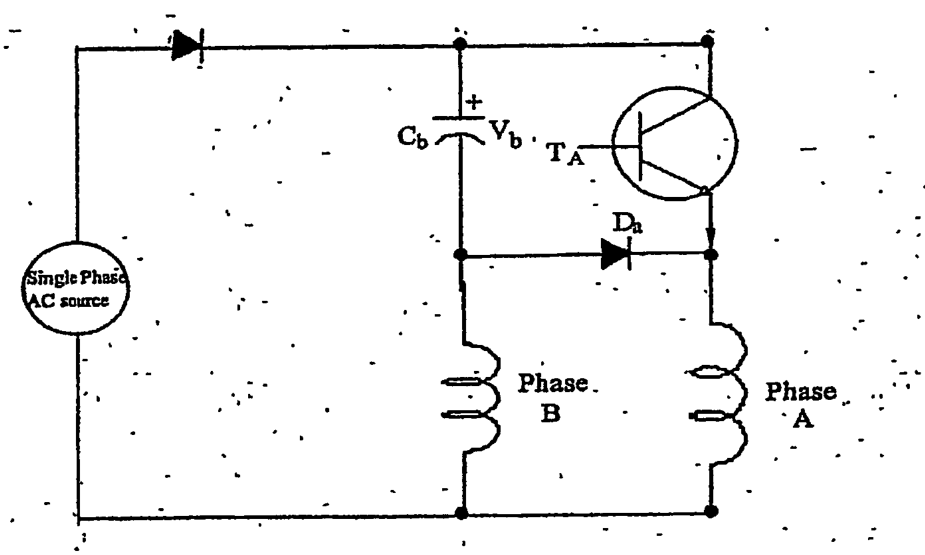


Fig. 10

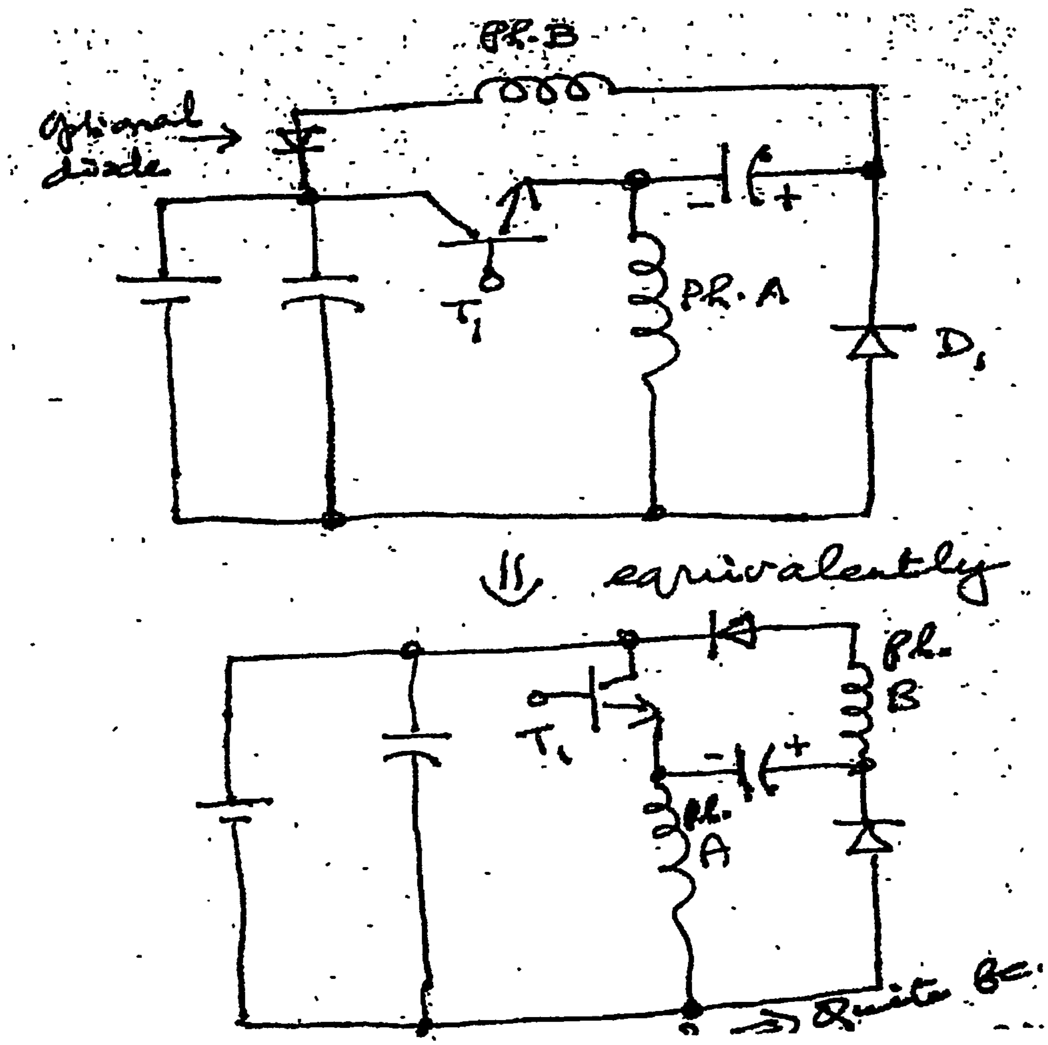

Ph. B
Optional diode
T_1
Ph. A
D_1
equivalently
Ph. B
T_1
Ph. A
Quite BC.

Fig. 11a

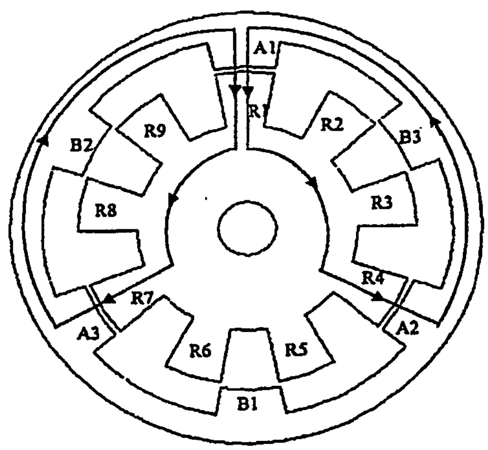


Fig. 11b

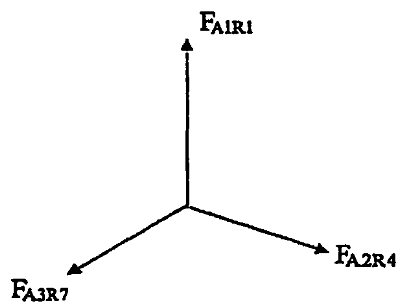


Fig. 12a

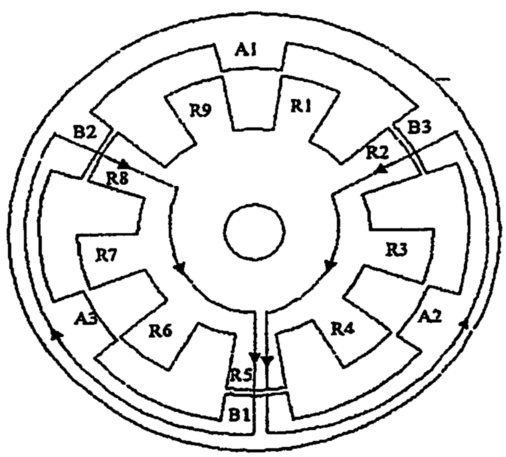


Fig. 12b

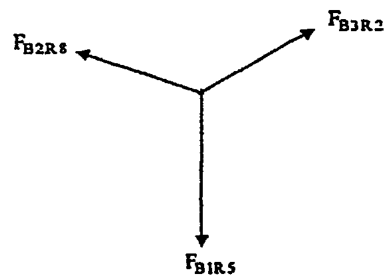


Fig. 13

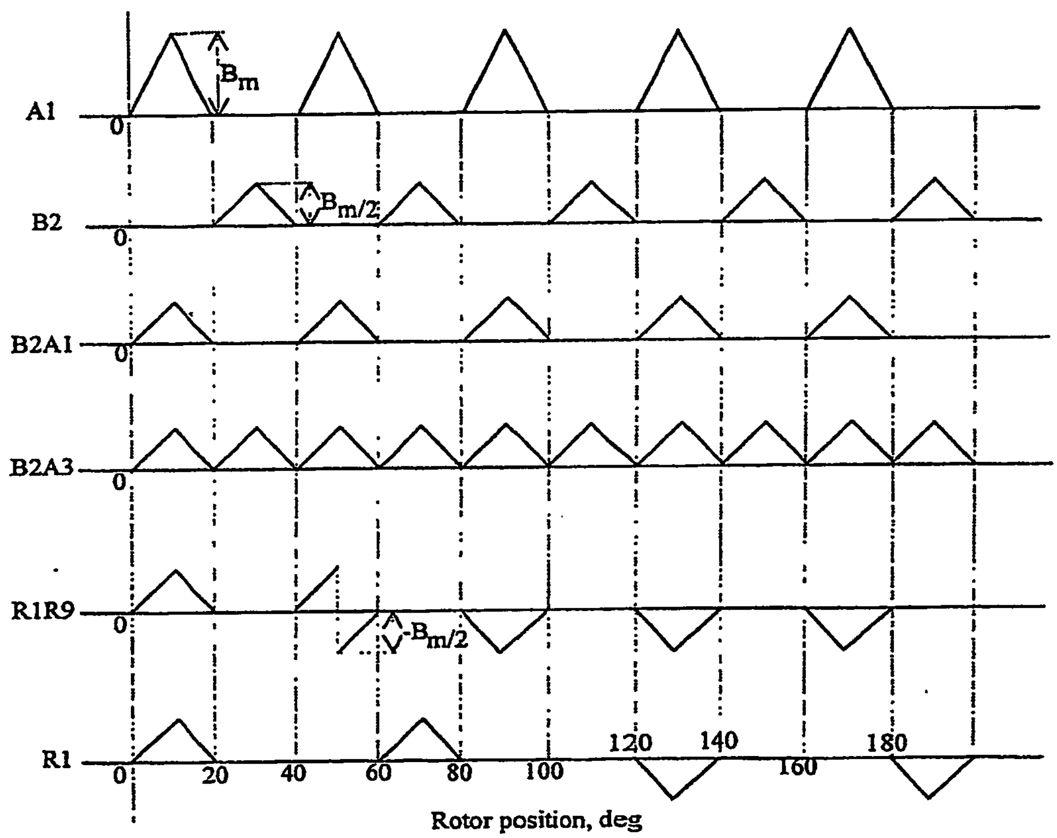

A1
B2
B2A1
B2A3
R1R9
R1
Bm
Bm/2
-Bm/2
0
20
40
60
80
100
120
140
160
180
Rotor position, deg

Fig. 14

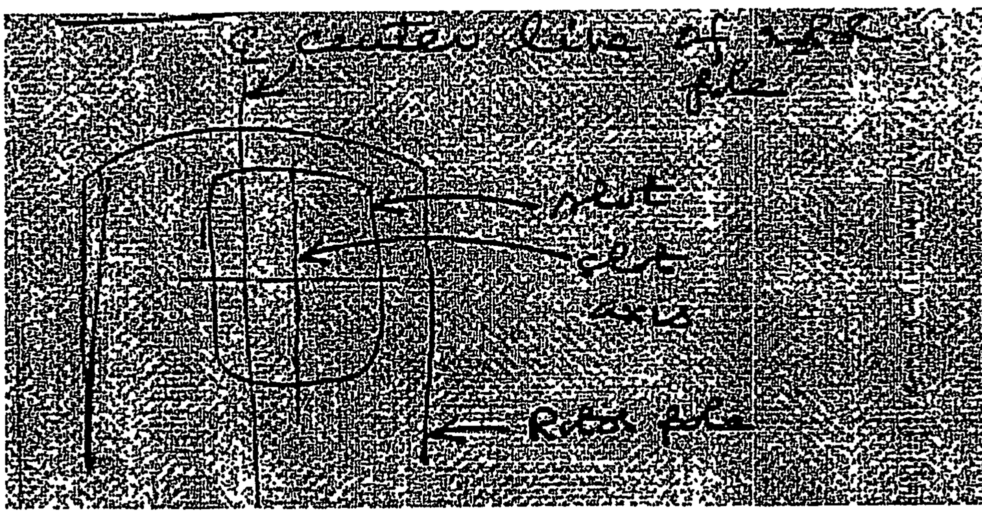


Fig. 15

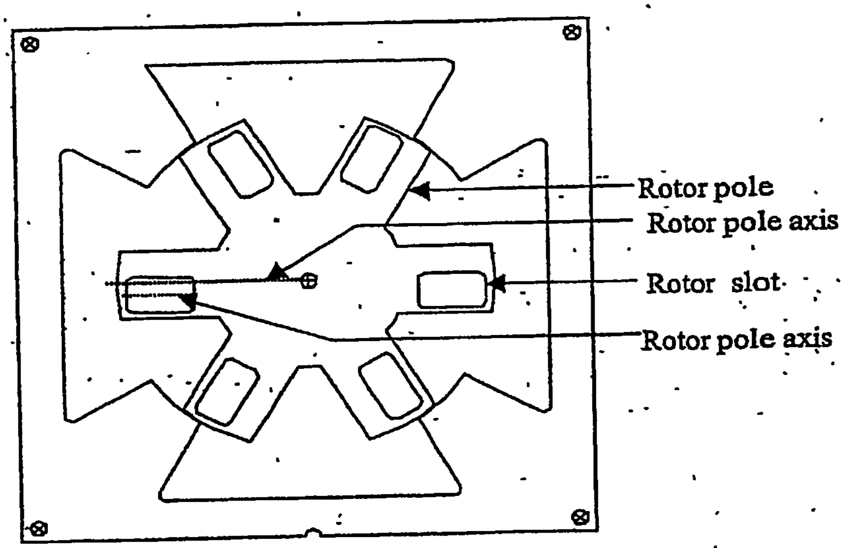


Fig. 16

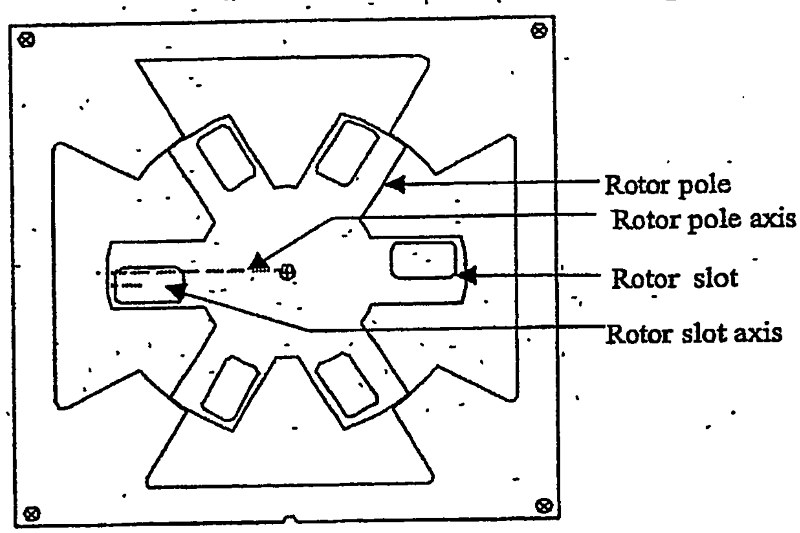


Fig. 17

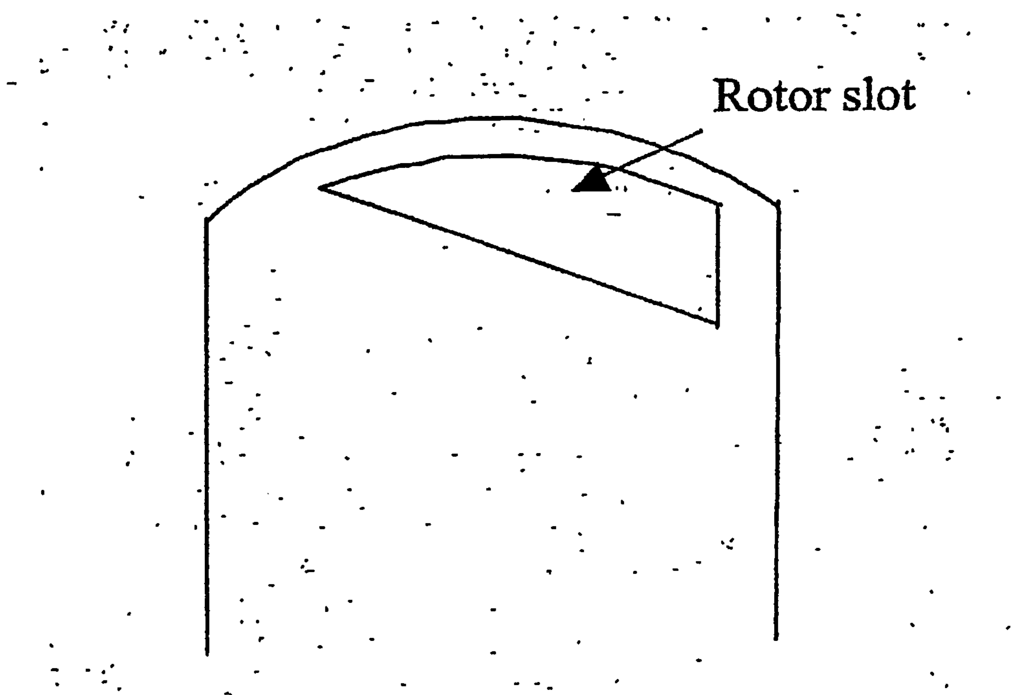


Fig. 18

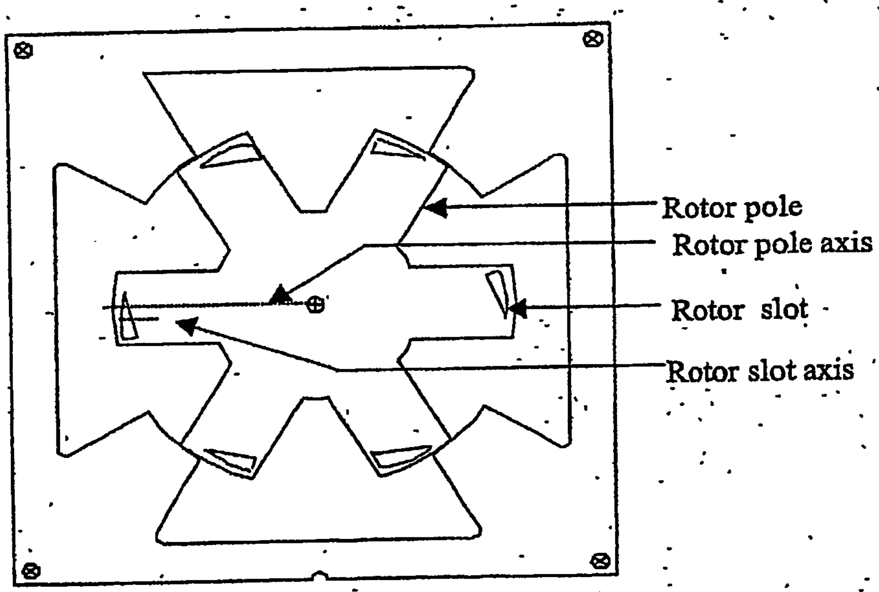


Fig. 19

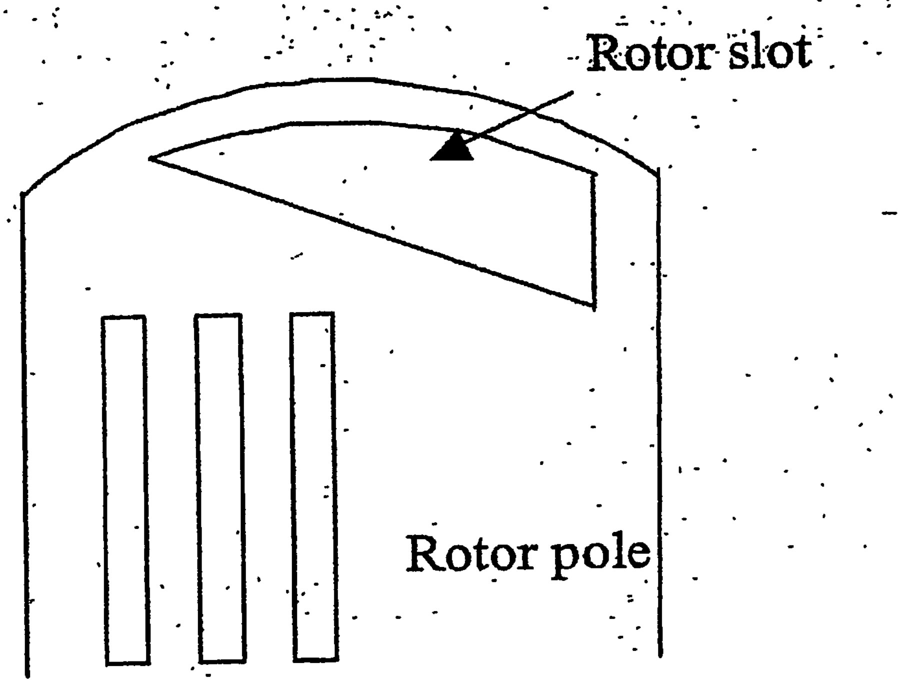


Fig. 20

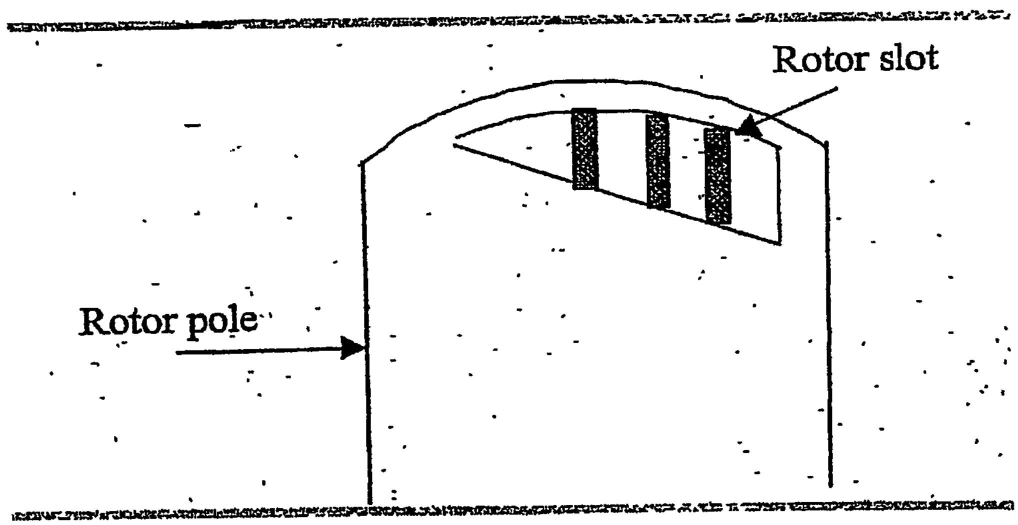


Fig. 21

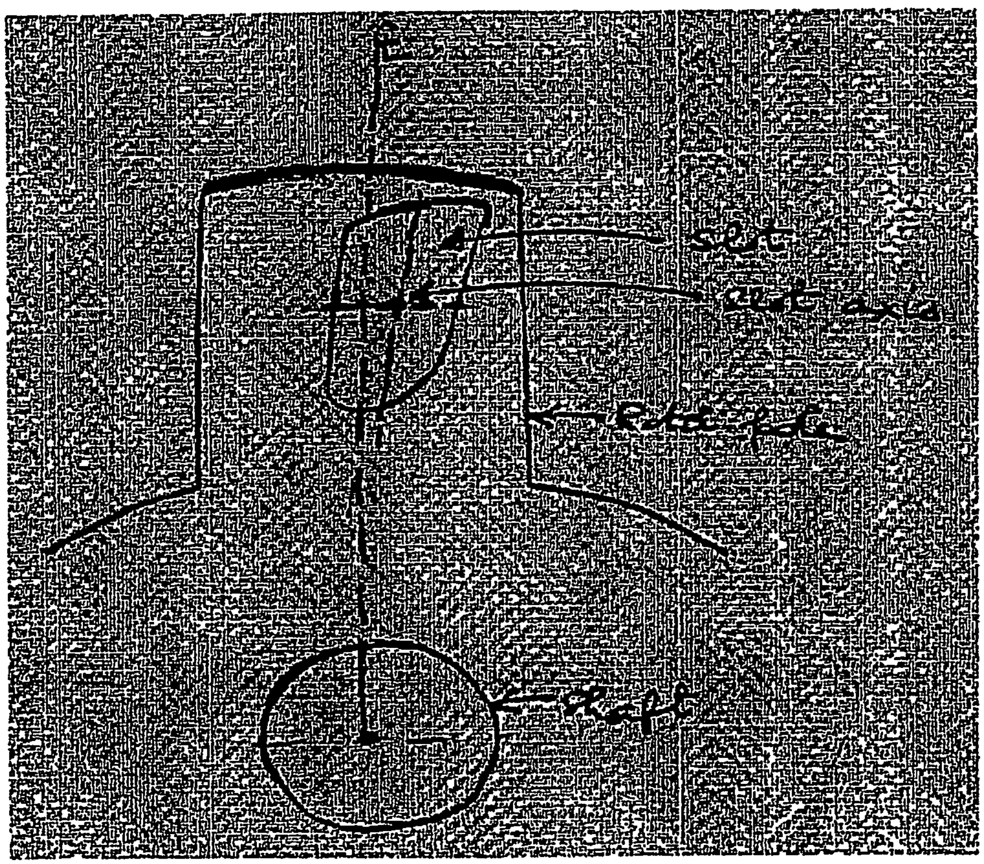


Fig. 22

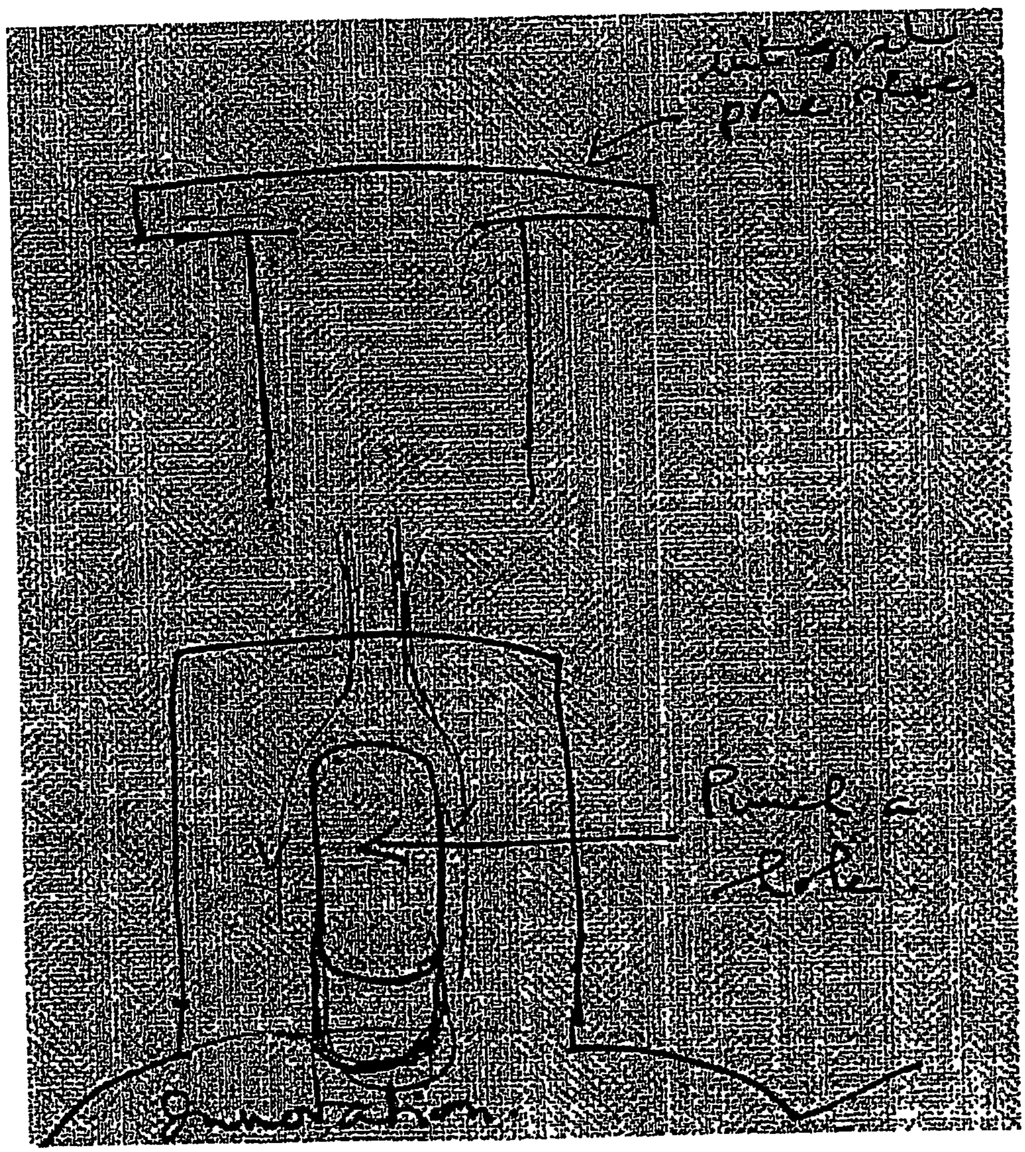


Fig. 23

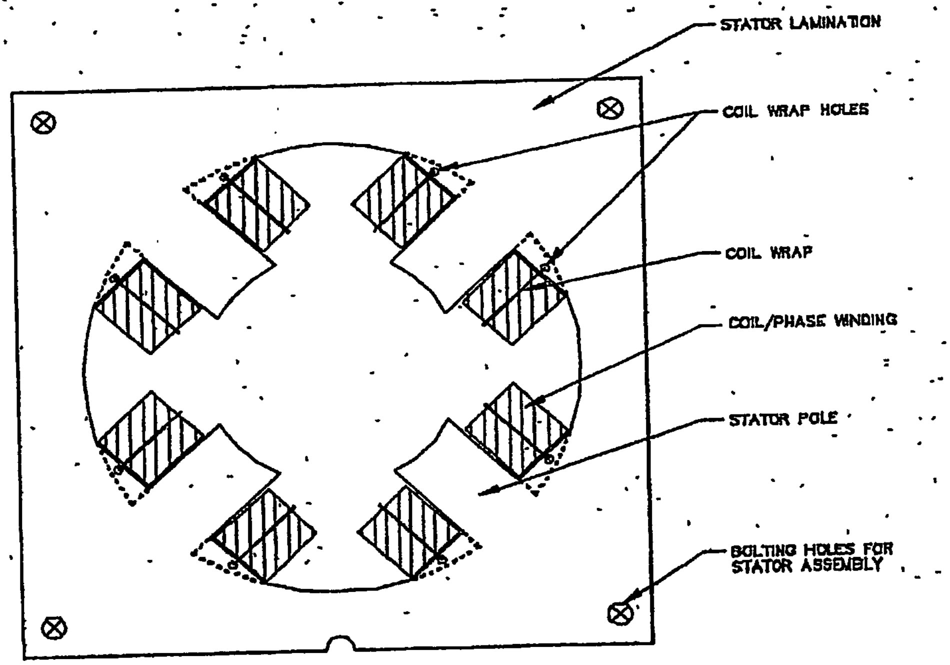

STATOR LAMINATION
COIL WRAP HOLES
COIL WRAP
COIL/PHASE WINDING
STATOR POLE
BOLTING HOLES FOR
STATOR ASSEMBLY

Fig. 24

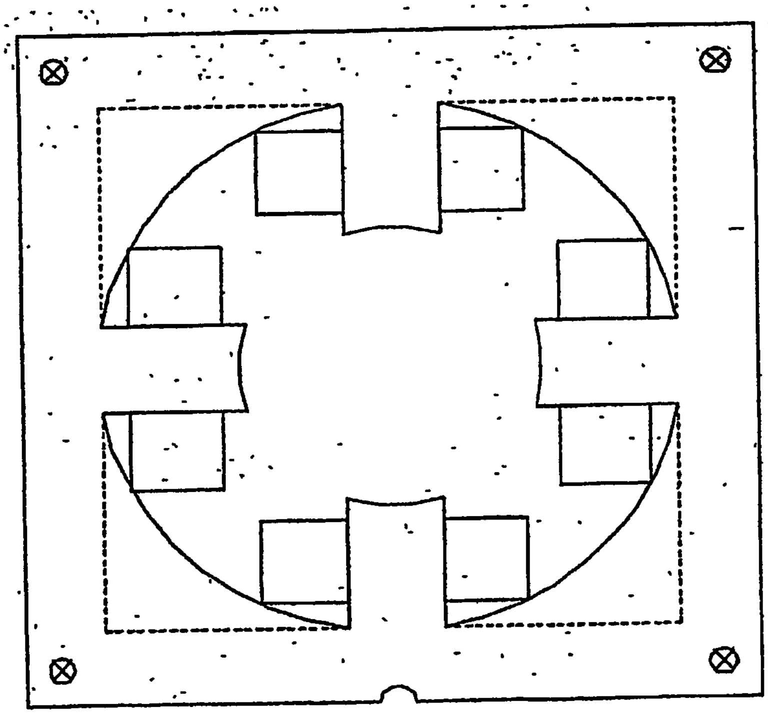


Fig. 25a

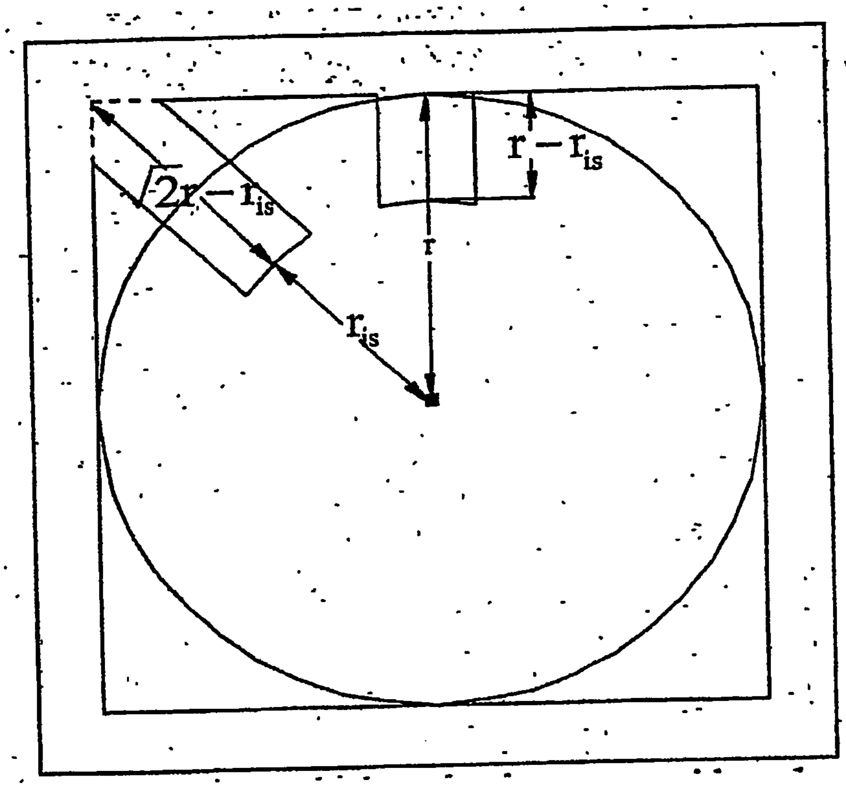


Fig. 25b

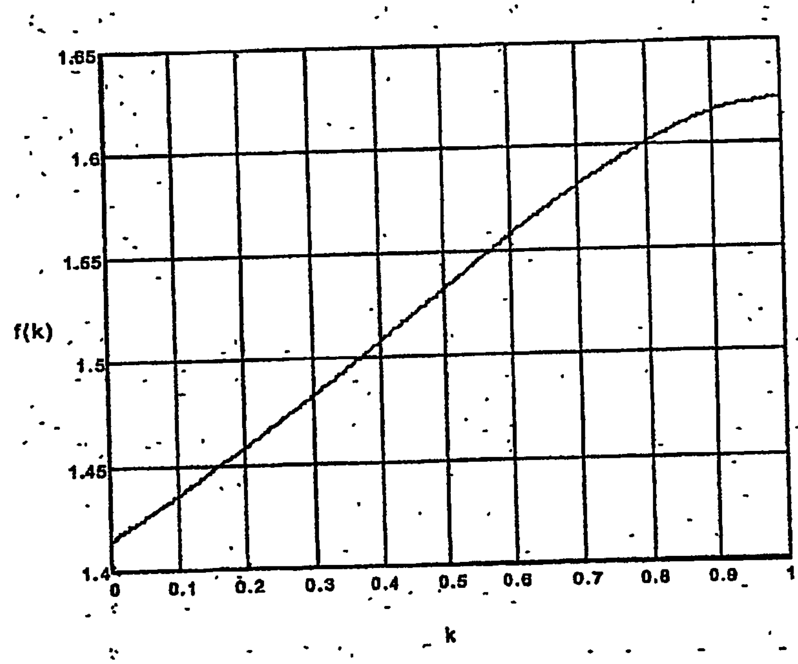


Fig. 26

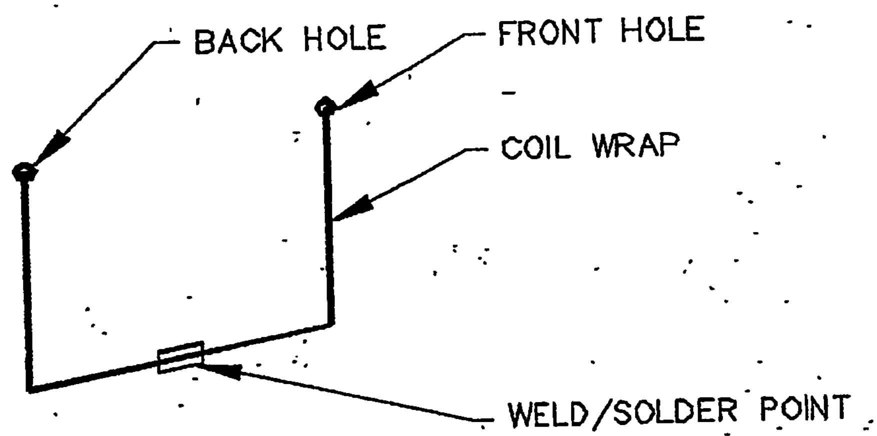


Fig. 27

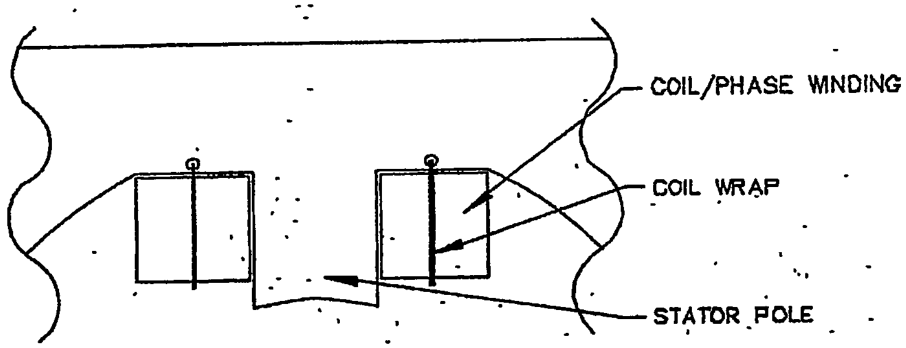
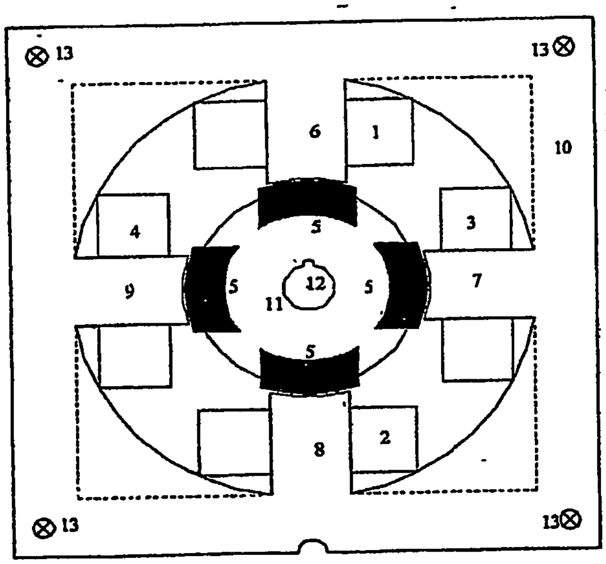
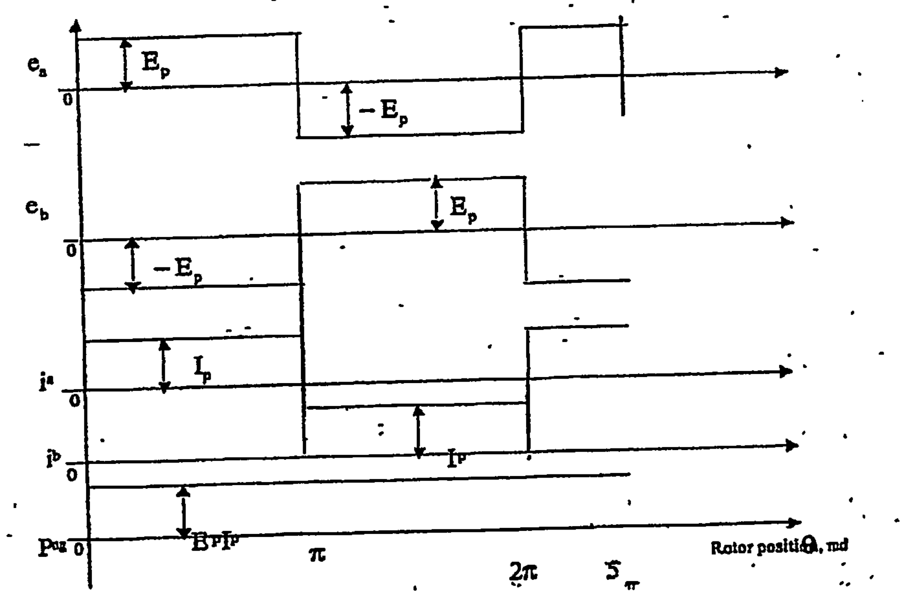


Fig. 28



1. Phase A winding top coil
2. Phase A winding bottom coil
3. Phase B winding top coil
4. Phase B winding bottom coil
5. Rotor permanent magnets
6,7,8 ,9 Stator teeth or poles
10. Stator back iron
11. Rotor back iron
12. Shaft
13. Stator bolting holes for assembly

Fig. 29a



e_a
E_p
0
$-E_p$
e_b
E_p
0
$-E_p$
i^a
I_p
0
i^b
I^p
0
P_{oa}
0
E^pI^p
π
2π
Rotor position, θ, rad

Fig. 29b

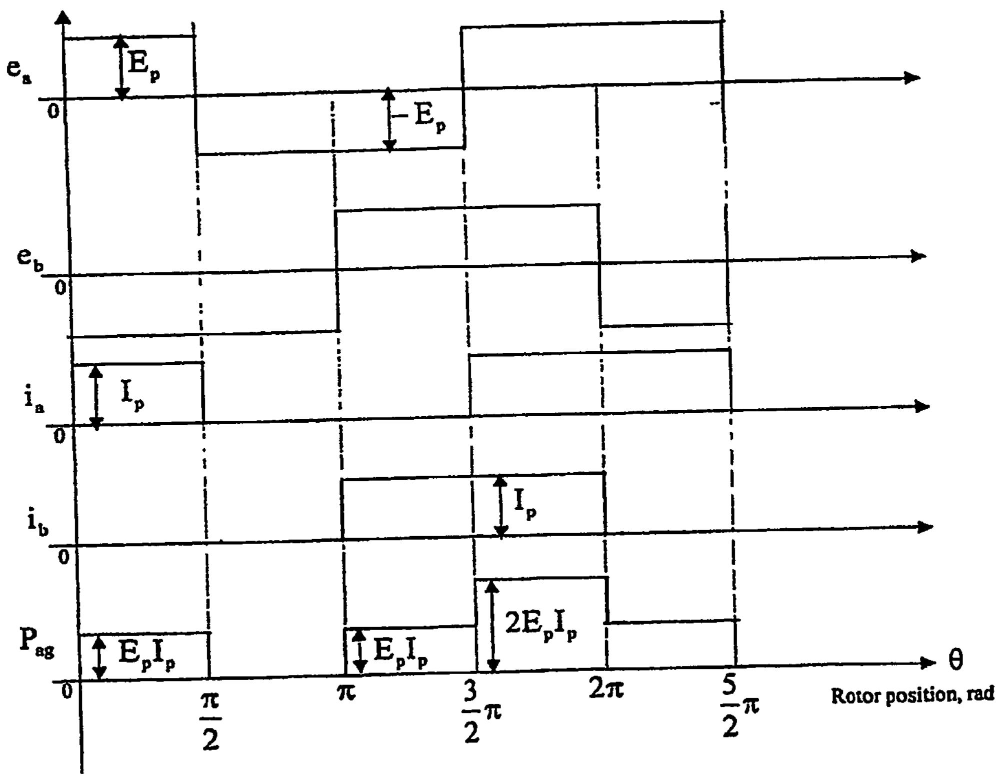

e_a
0
E_p
$-E_p$
e_b
0
i_a
0
I_p
i_b
0
I_p
P_{ag}
0
E_pI_p
E_pI_p
$2E_pI_p$
$\frac{\pi}{2}$
π
$\frac{3}{2}\pi$
2π
$\frac{5}{2}\pi$
θ
Rotor position, rad

Fig. 30

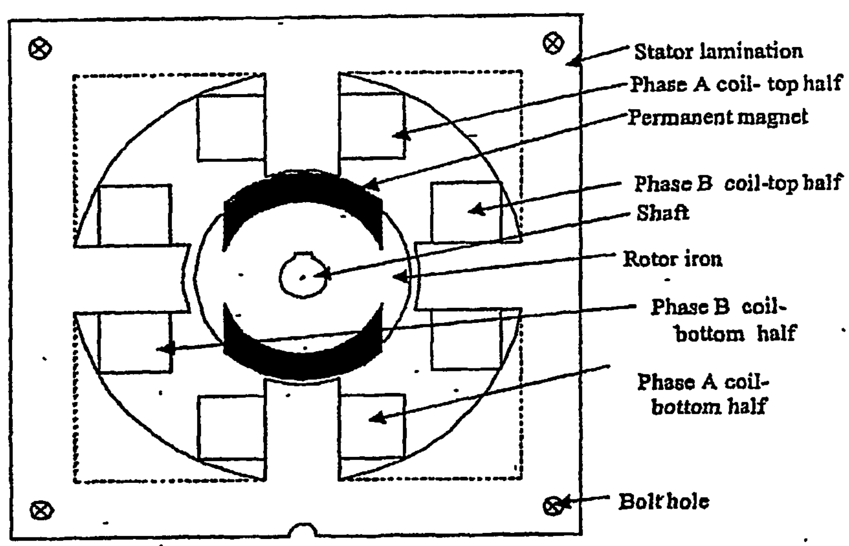

Stator lamination
Phase A coil- top half
Permanent magnet
Phase B coil-top half
Shaft
Rotor iron
Phase B coil-
bottom half
Phase A coil-
bottom half
Bolt hole

Fig. 31

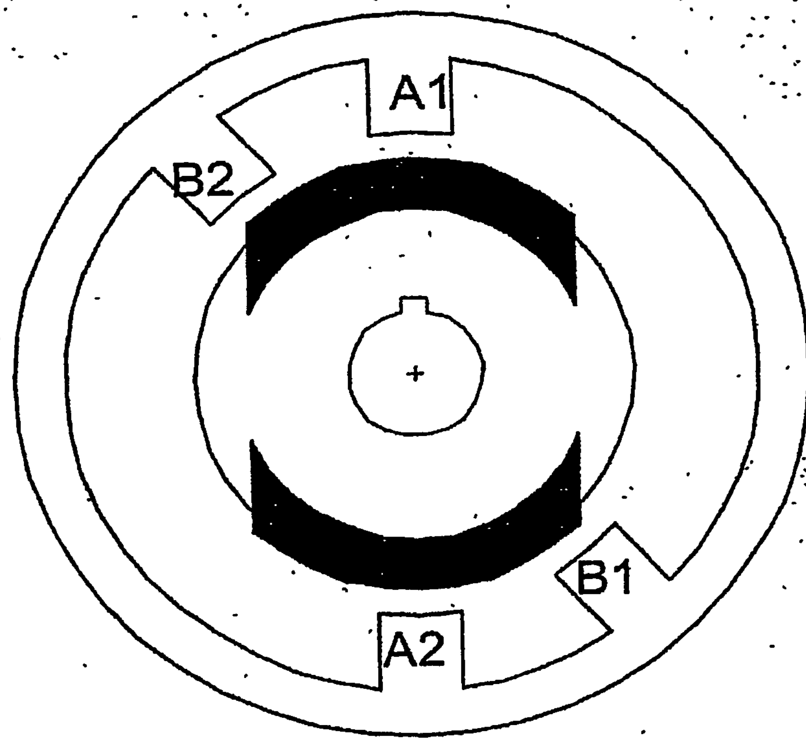


Fig. 32

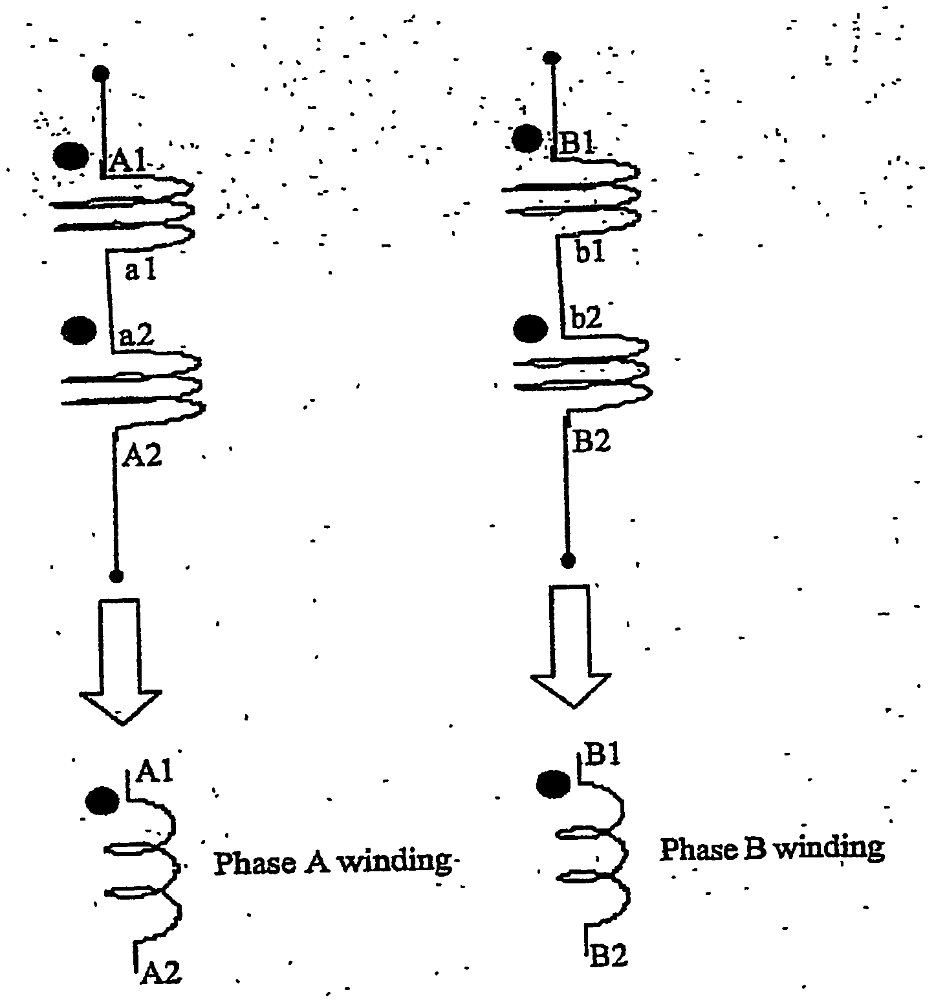

A1
a1
a2
A2
B1
b1
b2
B2
A1
A2
Phase A winding
B1
B2
Phase B winding

Fig. 33

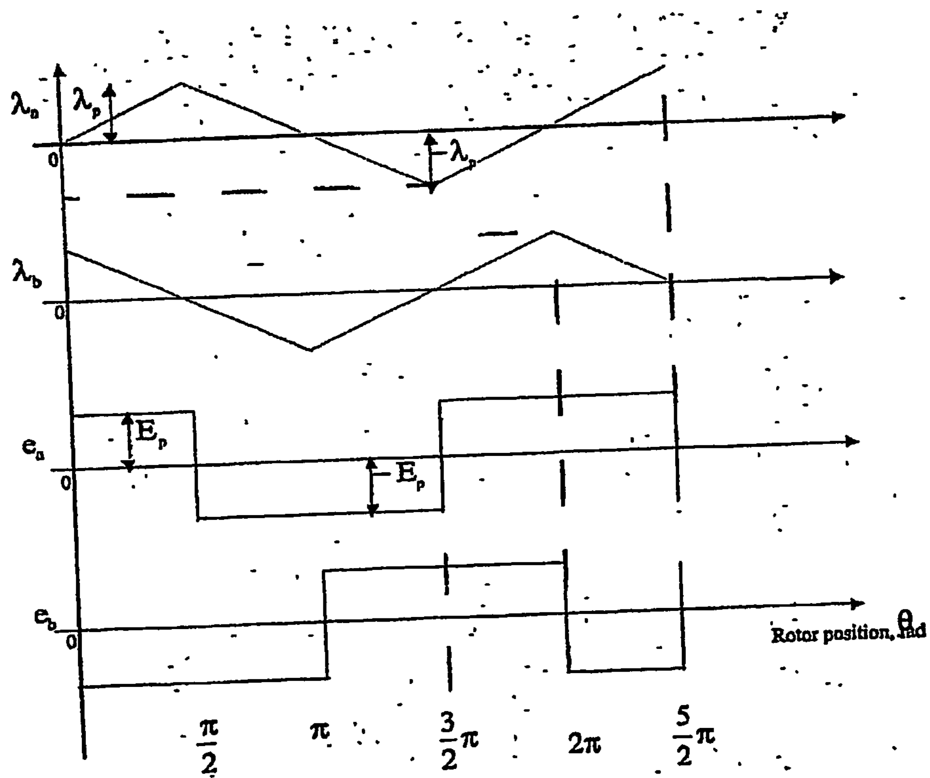

λ_a
λ_p
0
$-\lambda_p$
λ_b
0
e_a
E_p
0
$-E_p$
e_b
0
Rotor position, θ, rad
$\frac{\pi}{2}$
π
$\frac{3}{2}\pi$
2π
$\frac{5}{2}\pi$

Fig. 34

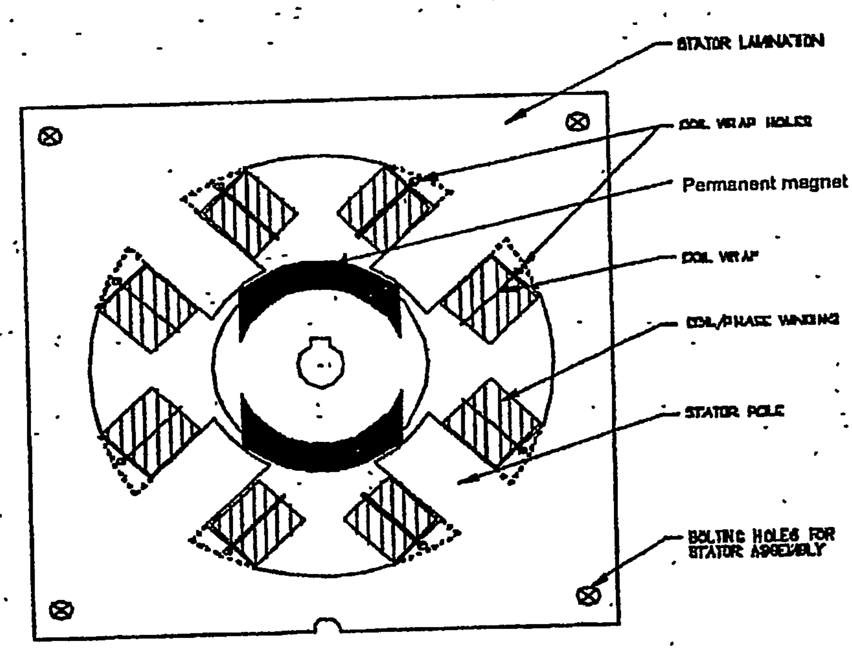

STATOR LAMINATION
COIL WRAP HOLES
Permanent magnet
COIL WRAP
COIL/PHASE WINDING
STATOR POLE
BOLTING HOLES FOR STATOR ASSEMBLY

Fig. 35

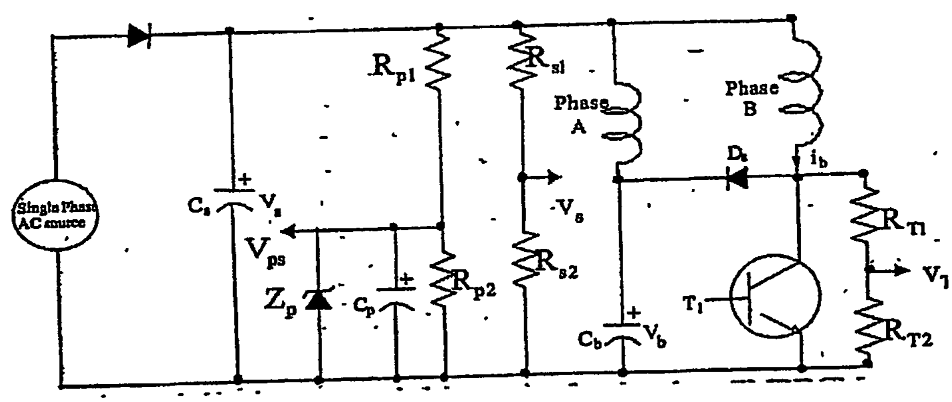

Single Phase AC source
C_s
V_s
V_{ps}
Z_p
C_p
R_{p1}
R_{p2}
R_{s1}
R_{s2}
V_s
Phase A
Phase B
D_s
i_b
C_b
V_b
T_1
R_{T1}
R_{T2}
V_1

Fig. 36

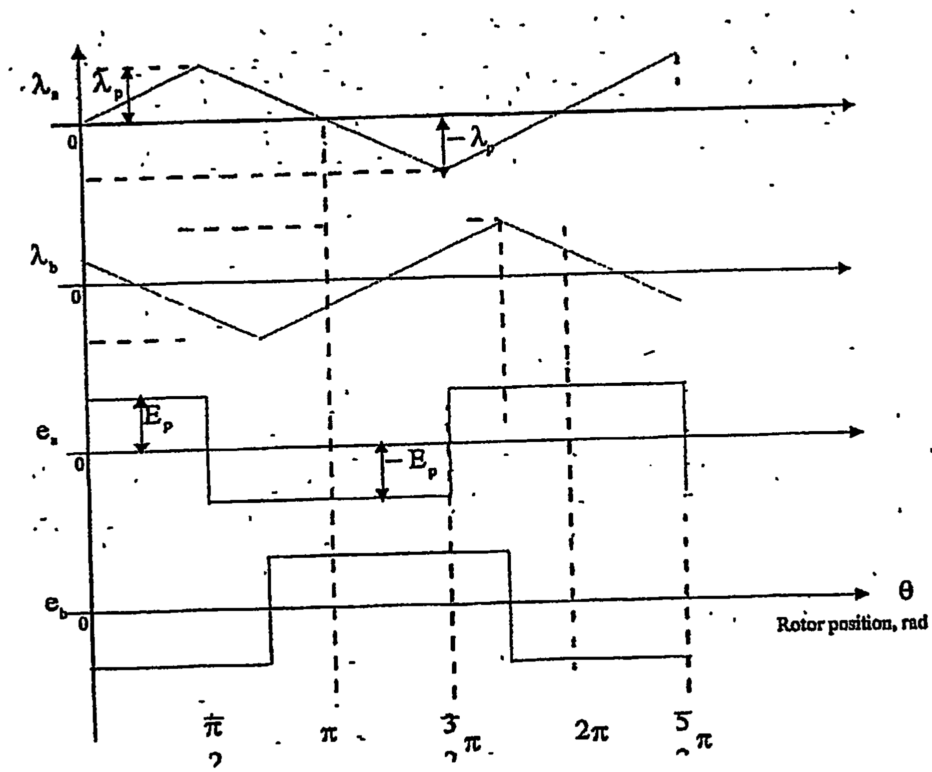

λ_a
λ_p
$-\lambda_p$
λ_b
e_a
E_p
$-E_p$
e_b
0
θ
Rotor position, rad
$\frac{\pi}{2}$
π
$\frac{3}{2}\pi$
2π
$\frac{5}{2}\pi$

Fig. 37

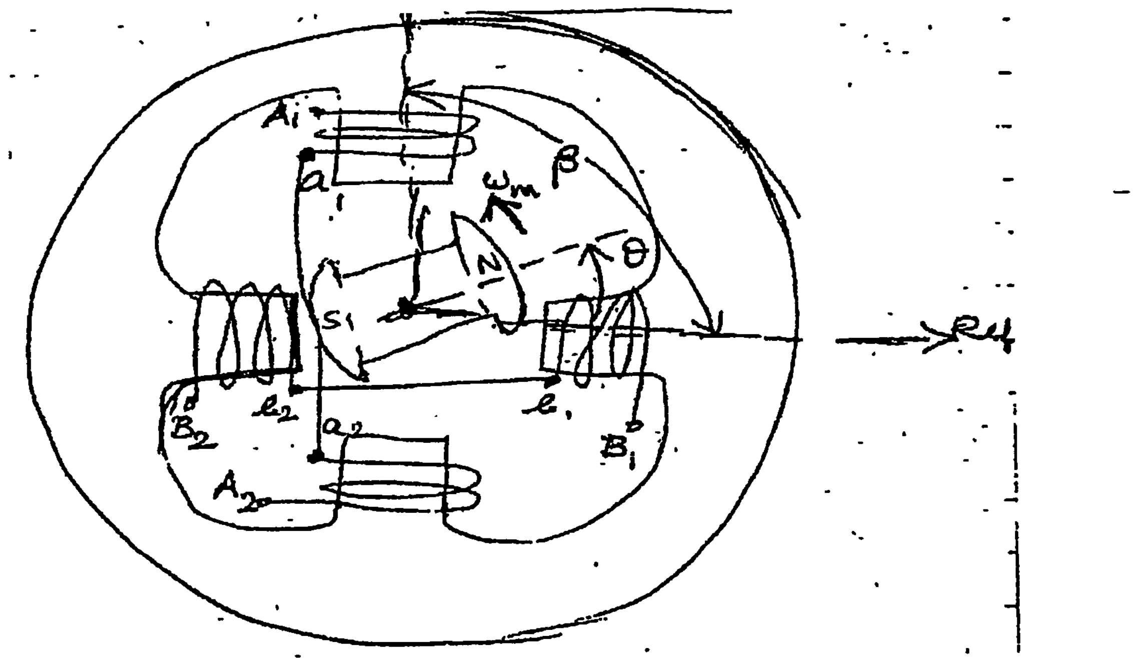


Fig. 38

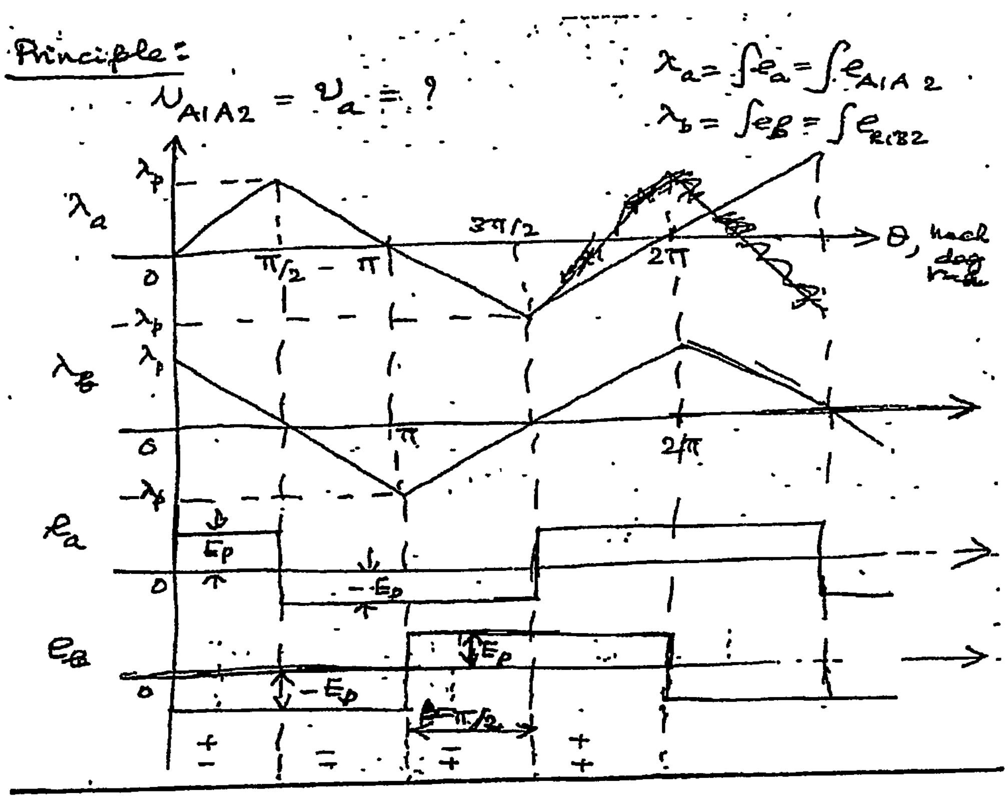

Principle:
$v_{A1A2} = v_a = ?$
$\lambda_a = \int e_a = \int e_{A1A2}$
$\lambda_b = \int e_B = \int e_{B1B2}$
λ_a
λ_p
$-\lambda_p$
0
$\pi/2$
π
$3\pi/2$
2π
θ
λ_B
e_a
E_p
$-E_p$
e_B
$\pi/2$
+
-

Fig. 39

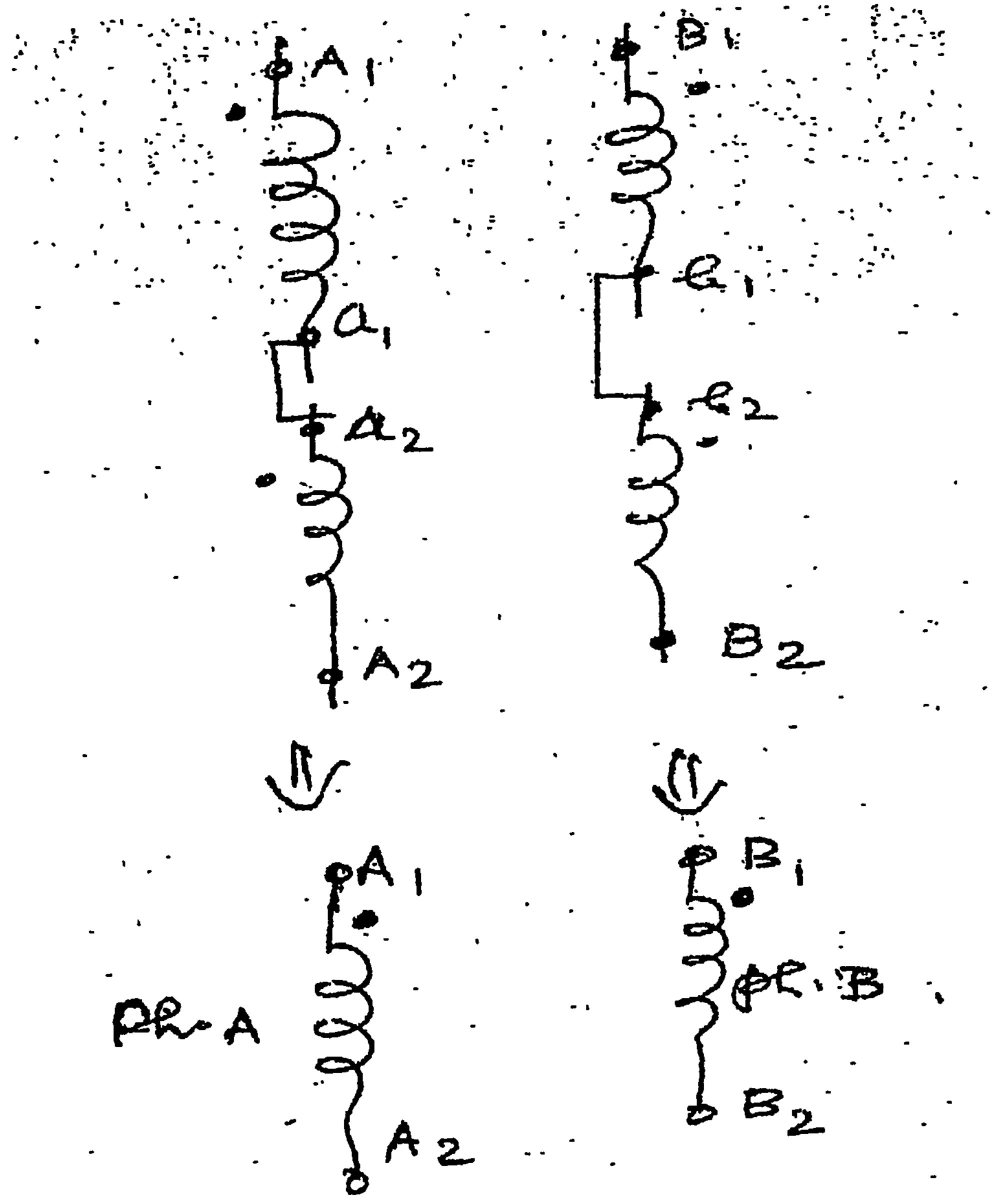
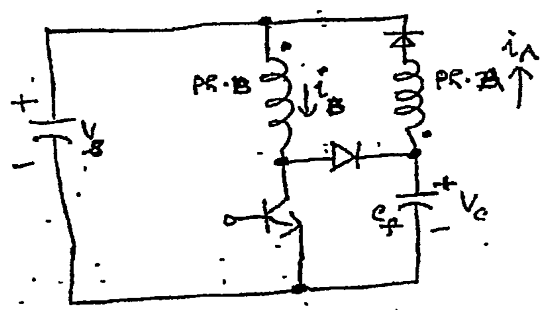


Fig. 40

Consider ph seq BA (i.e., CW rotation)

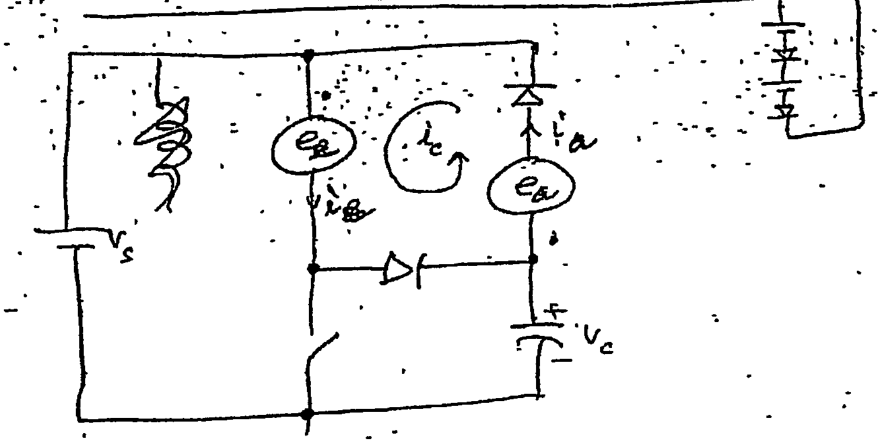


If $v_C \geq V_s + E_p$, then $i_B = 0$ during negative half cycle of ph. B.

$$\therefore V_c\Big|_{min} = V_s + E_p$$

Fig. 41

Consider the [illegible] situation for given winding polarities



$e_B \Rightarrow +$, $V_C = V_s + e_B \Rightarrow$ drive i_B

$e_B \Rightarrow +$, $e_A \Rightarrow -ve$, $i_c = 0$

$e_B \Rightarrow +$, $e_A \Rightarrow +ve$, $i_c = 0$

$e_A \Rightarrow +ve$, $V_c > e_A + V_s$ for $i_a > 0$, i_a reduced

$e_A \Rightarrow -ve$, $V_c + e_A \Rightarrow$ will drive i_a, i_a increased
-ve voltage, +ve current $\Rightarrow$ -ve torque
not desirable

Fig. 42

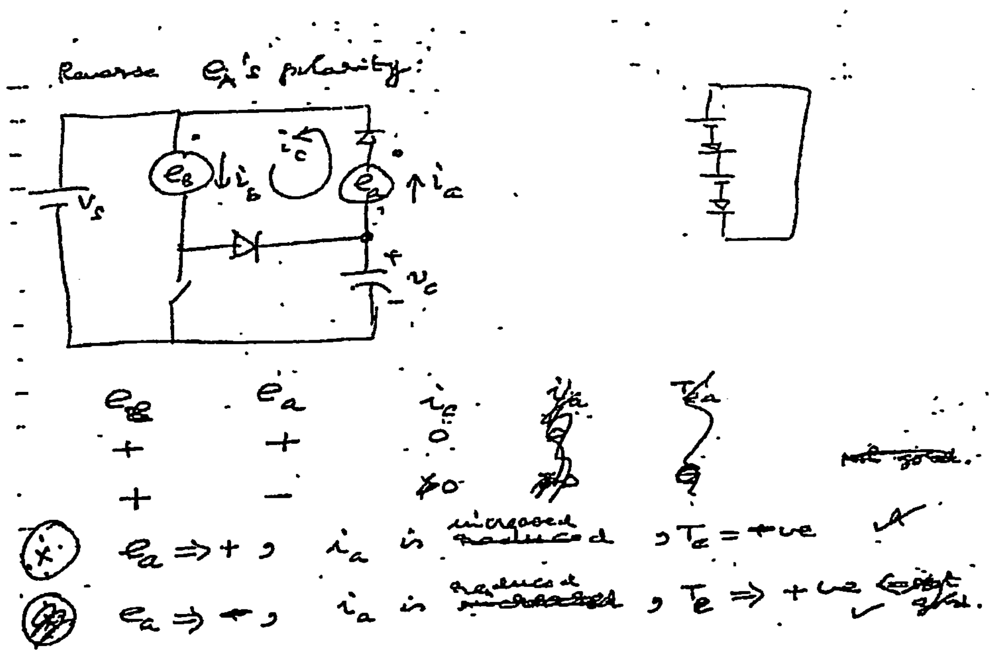
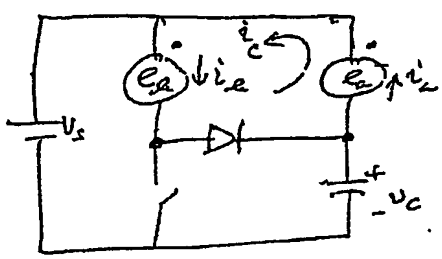
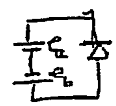


Fig. 43

Suppose reverse diode in e_a's place.



e_b	e_a	i_c
+	+	0
+	−	0
−	−	0
−	+	>0 (if $\lvert e_b \rvert > e_a$)



$e_a \Rightarrow +$, $i_a \Rightarrow$ ~~small~~ high, $T_e \Rightarrow -$

$e_a \Rightarrow -$, $i_a \Rightarrow$ small, $T_e \Rightarrow +$

or $e_a \Rightarrow +$, & $v_c + e_a > v_s \Rightarrow i_a \Rightarrow$ ~~+~~ high, $T_e \Rightarrow +$ not good

small

$e_a \Rightarrow -$, $v_c > v_s + \lvert e_a \rvert \Rightarrow i_a \Rightarrow +$, $T_e \Rightarrow +$

Fig. 44

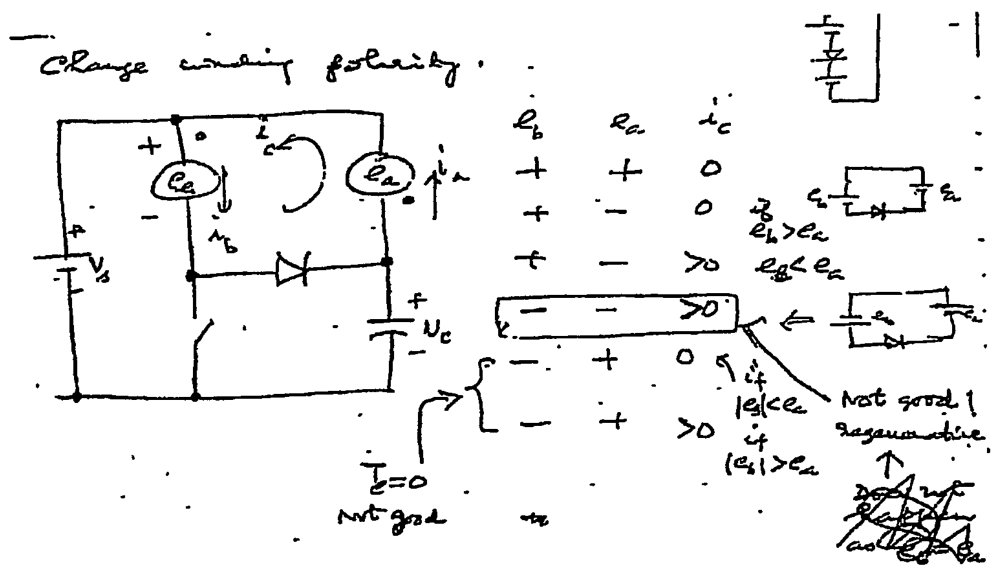

Change winding polarity.
Vs
Vc
Not good !
regenerative
Not good

Fig. 45

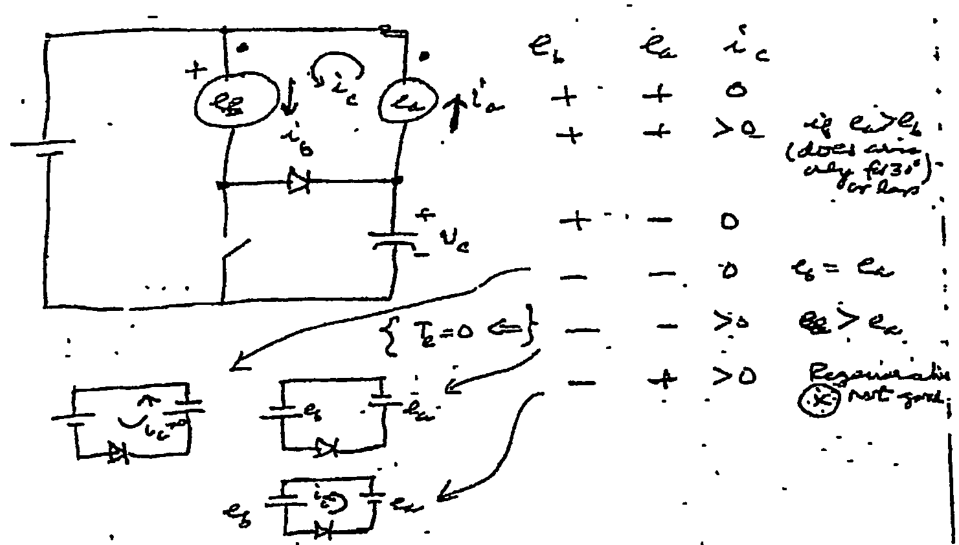
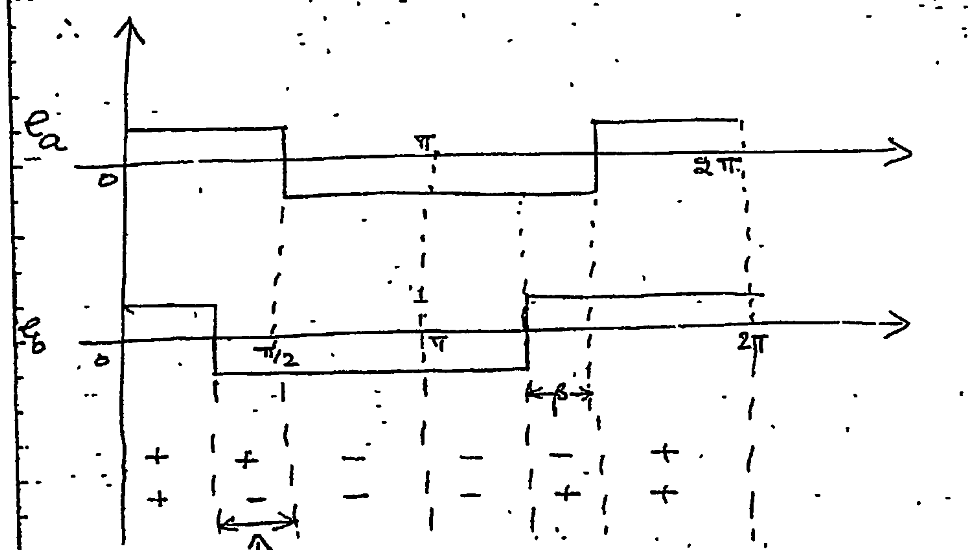


Fig. 46

One solution to reduce the undesirable periods of e_b, e_a {−, +} that contributes to regeneration is to have a phase shift of two phases by less than (or more than 90° ⟹ say, 145 to 150°).

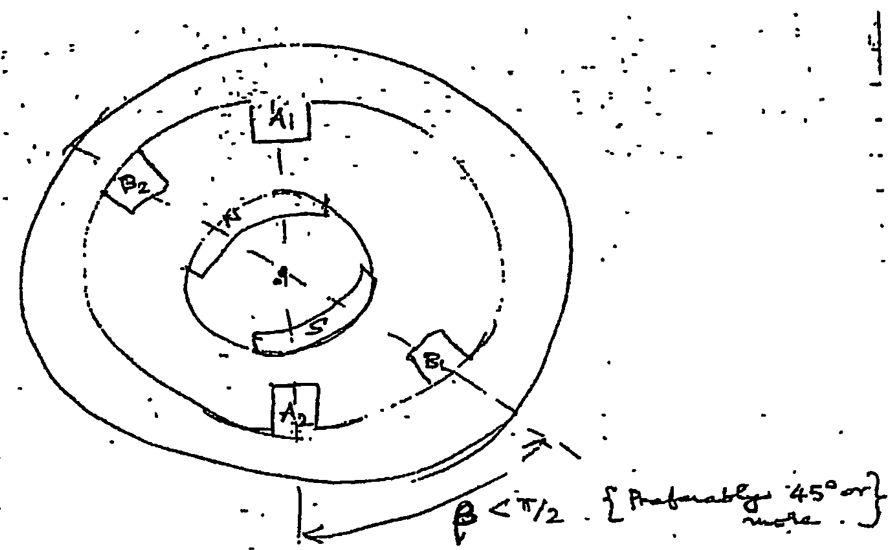
∴



This period is reduced as β is reduced.

∴ A phase shift of β between phases A and B is required to maximize the torque output.

Fig. 47



- Main phase : B
- Aux. phase : A
- Torque at all times (+ or −) ⇒ nonzero.
- ∴ starting ~~in~~ any direction and four quadrant operation not possible.

Control strategy for starting and running has to be developed.

Fig. 48

Control strategy:

(i) FM (forward motoring)

At standstill,

ⓐ $B_a > 0$, (i.e. $e_b > 0$) e_b & $e_a > 0$

Turn on switch, $i_b > 0$, $T_e > 0$.

Rotor moves forward.

ⓑ If $B_b < 0$, ($e_b < 0$) & $e_a > 0$, then

Turn on T_1 & charge v_c

that will retard the rotor & hence changing rotor position ideal for starting.

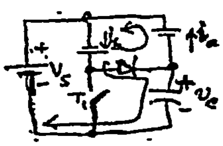
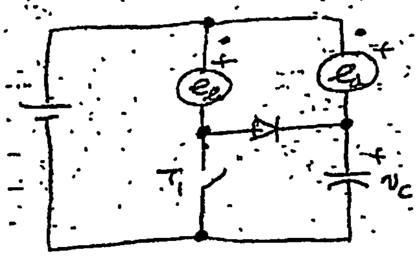


Fig. 49



(c) $e_b = -$, $e_a = -$

Try (e) + $i_a \Rightarrow -$, $\therefore T_e \Rightarrow +$, Rotor will move forward.

(d) All conditions for forward starting are satisfied.

(ii) RM (Reverse motoring)

Similar technique as in (i) but need to make sure rotor is set rotating in reverse direction.

(iii) FR (Forward regeneration) {when rotor is in CW direction of rotation}

when $e_b < 0$, turn on T_1.

(iv) RR (Reverse regeneration). {when rotor is rotating in CCW}

when $e_b < 0$, turn on T_1

A four quadrant drive with a single switch converter and 2 ph winding brushless PMBDC is achieved.

Similarly write a disclosure for the control of 2ph SRM with a single switch converter topology.

The auxiliary windings need not be of the same wire size and same number of turns as the main phase.

CLAIMS

What is claimed is:

1. A two-phase switched reluctance machine (TPSRM), comprising:

a stator having a plurality of poles and a ferromagnetic or iron back material; and

a rotor having a plurality of poles and a ferromagnetic or iron back material, wherein:

current flowing through coils wound around a first set of the plurality of stator poles induces a flux flow through the first set of stator poles and portions of the stator back material during a first excitation phase,

current flowing through coils wound around a second set of the plurality of stator poles induces a flux flow through the second set of stator poles and portions of the stator back material during a second excitation phase, and

the numbers of stator and rotor poles are selected such that substantially no flux reversal occurs in any part of the stator back material as a result of transitioning between the first and second excitation phases.

2. The TPSRM of claim 1, wherein the number of stator poles is 6 and the number of rotor poles is 3.

3. The TPSRM of claim 1, wherein the number of stator poles is 6 and the number of rotor poles is 9.

4. The TPSRM of claim 1, wherein the number of stator poles is 6 and the number of rotor poles is 15.

5. The TPSRM of claim 1, wherein the stator or rotor poles provide a non-zero combined torque for all rotational positions of the rotor during which at least one of the first and second phases is excited or a transition is occurring between the first and second phase excitations.

6. The TPSRM of claim 5, wherein the distal end faces of the stator or rotor poles are contoured to have a non-uniform radius from the rotor's axis of rotation.

7. The TPSRM of claim 5, wherein the rotor poles are slotted.

8. The TPSRM of claim 1, wherein one stator pole in each of the first and second sets has a maximum flux density flow rate that is about twice the maximum flux density flow rate of the other stator poles in the set.

9. The TPSRM of claim 1, wherein one stator pole in each of the first and second sets conveys about twice or more the amount of flux density conveyed by the other stator poles in the set.

10. The TPSRM of claim 1, wherein the coil wound around one stator pole in each of the first and second sets has twice the number of windings as the coils wound around the other stator poles in the set.

11. The TPSRM of claim 1, wherein further comprising a controller that provides about twice as much current to the coil wound around one stator pole in each of the first and

second sets as is provided to the other stator poles in the set.

12. The TPSRM of claim 1, wherein the numbers of stator and rotor poles are further selected such that a flux reversal occurs only once in any part of the rotor back material, excluding the rotor poles, per revolution of the rotor as a result of transitioning between the first and second excitation phases.

13. The TPSRM of claim 1, wherein the vector sum of normal forces exerted by the stator poles, in response to the first and second excitation phases, at any instant of time is zero.

14. A two-phase switched reluctance machine (TPSRM), comprising:

a stator having a plurality of poles and a ferromagnetic or iron back material; and

a rotor having a plurality of poles and a ferromagnetic or iron back material, wherein:

current flowing through coils wound around a first set of the plurality of stator poles induces a flux flow through the first set of stator poles and portions of the stator back material during a first excitation phase,

current flowing through coils wound around a second set of the plurality of stator poles induces a flux flow through the second set of stator poles and portions of the stator back material during a second excitation phase, and

the numbers of stator and rotor poles are selected such that a flux induced by each of the first and second excitation phases flows through a path encompassing about two-thirds of the circumference of each of the rotor and stator back materials.

15. A method of operating a two-phase switched reluctance machine (TPSRM), comprising:

inducing an electromagnetic flux to flow through a first set of poles of a stator of the TPSRM during a first excitation phase;

inducing an electromagnetic flux to flow through a second set of poles of the stator during a second excitation phase; and

transitioning between the first and second excitation phases without creating a substantial flux reversal in a ferromagnetic or iron back material of the stator.

16. The method of claim 15, wherein the electromagnetic flux induces a torque to a rotor of the TPSRM and the combined torque provided by both the first and second excitation phases produces a non-zero value for all rotational positions of the rotor during which at least one of the first and second phases is excited or a transition is occurring between the first and second phase excitations.

17. The method of claim 15, wherein one stator pole in each of the first and second sets has a maximum flux density

flow rate that is about twice the maximum flux density flow rate of the other stator poles in the set.

18. The method of claim 15, further comprising inducing about twice as much flux density to flow in one stator pole in each of the first and second sets as flows in the other stator poles in the set.

19. The method of claim 15, wherein a flux reversal substantially occurs only once in any part of a ferromagnetic or iron back material of a rotor of the TPSRM, excluding poles of the rotor, per revolution of the rotor as a result of transitioning between the first and second excitation phases.

20. The method of claim 15, further comprising regulating the electromagnetic flux flow through the stator poles during each of the first and second excitation phases to exert substantially a zero value vector sum of normal forces by the stator poles at any instant of time during the first or second excitation phases.

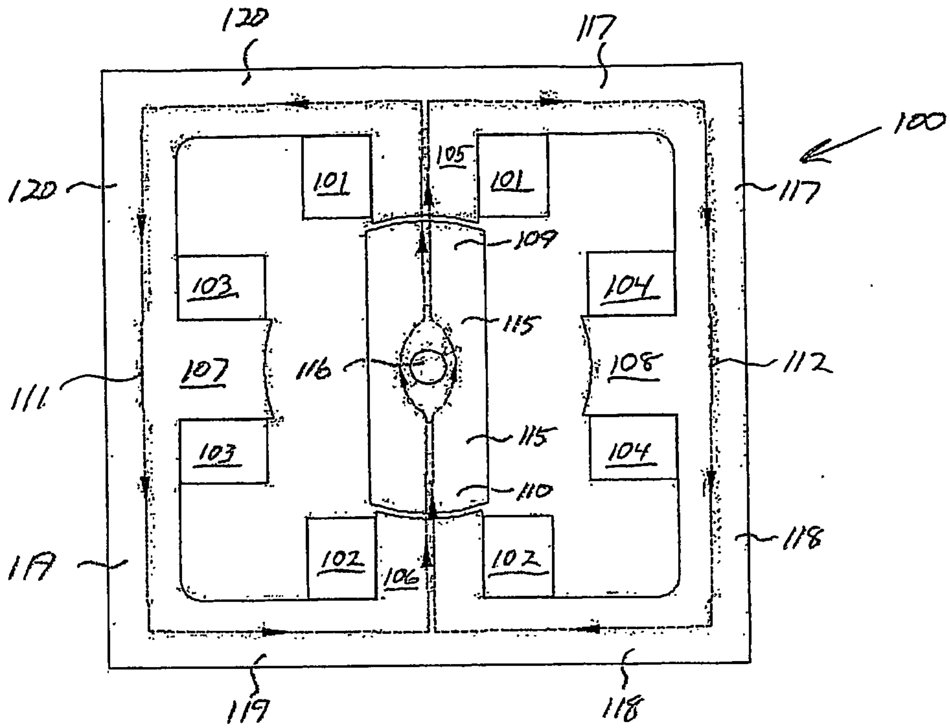

120
117
100
105
101
101
120
117
109
103
104
115
107
108
111
116
112
115
103
104
110
102
102
119
106
118
119
118

FIG. 1

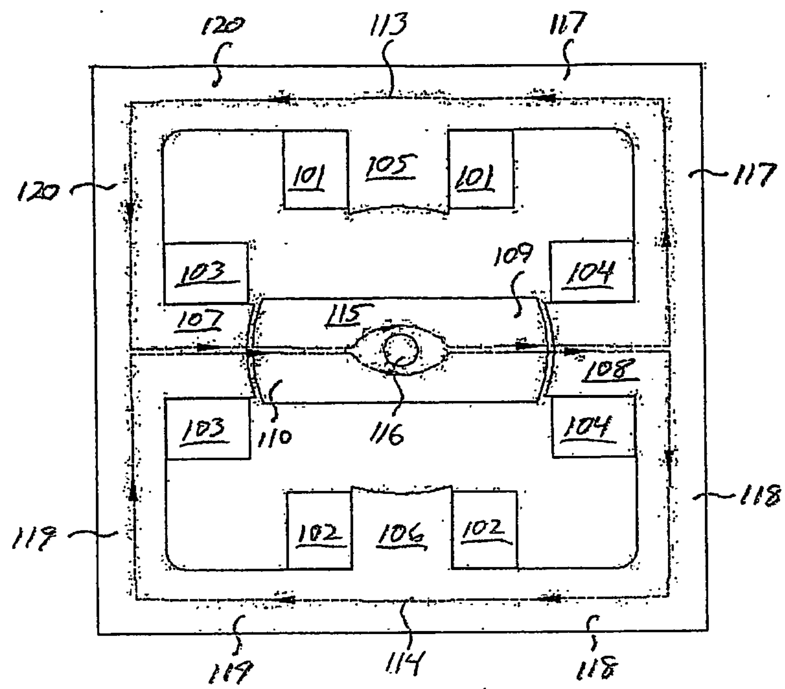
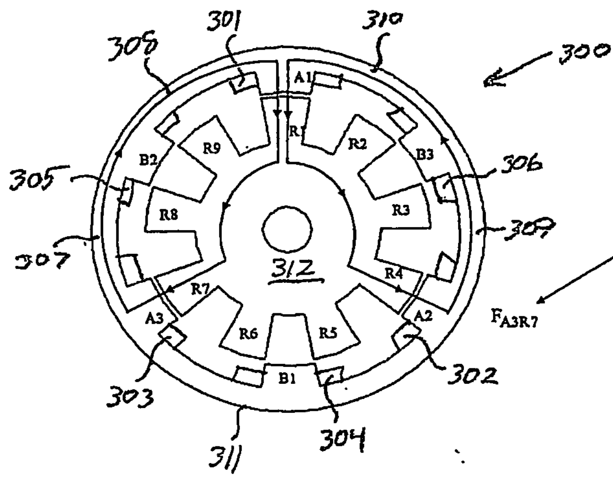
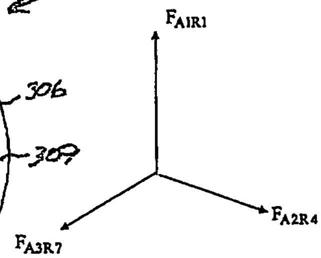

120
113
117
120
117
101
105
101
103
109
104
107
115
108
103
110
116
104
118
119
102
106
102
119
114
118

FIG. 2



300
301
310
308
305
306
307
309
312
303
302
311
304
A1
A2
A3
B1
B2
B3
R1
R2
R3
R4
R5
R6
R7
R8
R9

FIG. 3A



F_{A1R1}
F_{A2R4}
F_{A3R7}

FIG. 3B

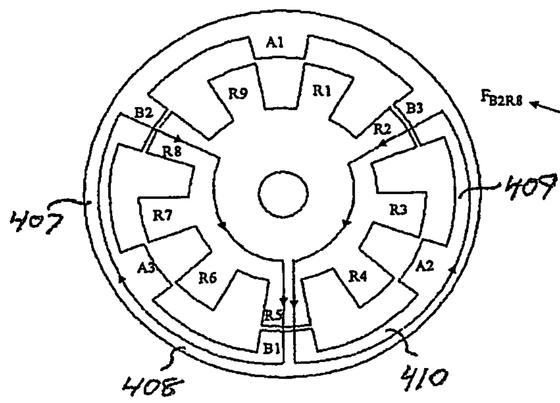

A1
R9
R1
B2
B3
R8
R2
407
409
R7
R3
A3
A2
R6
R4
R5
B1
408
410

FIG. 4A

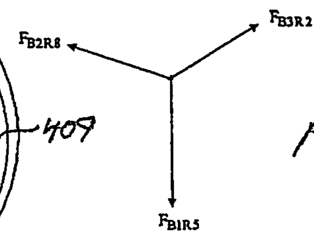
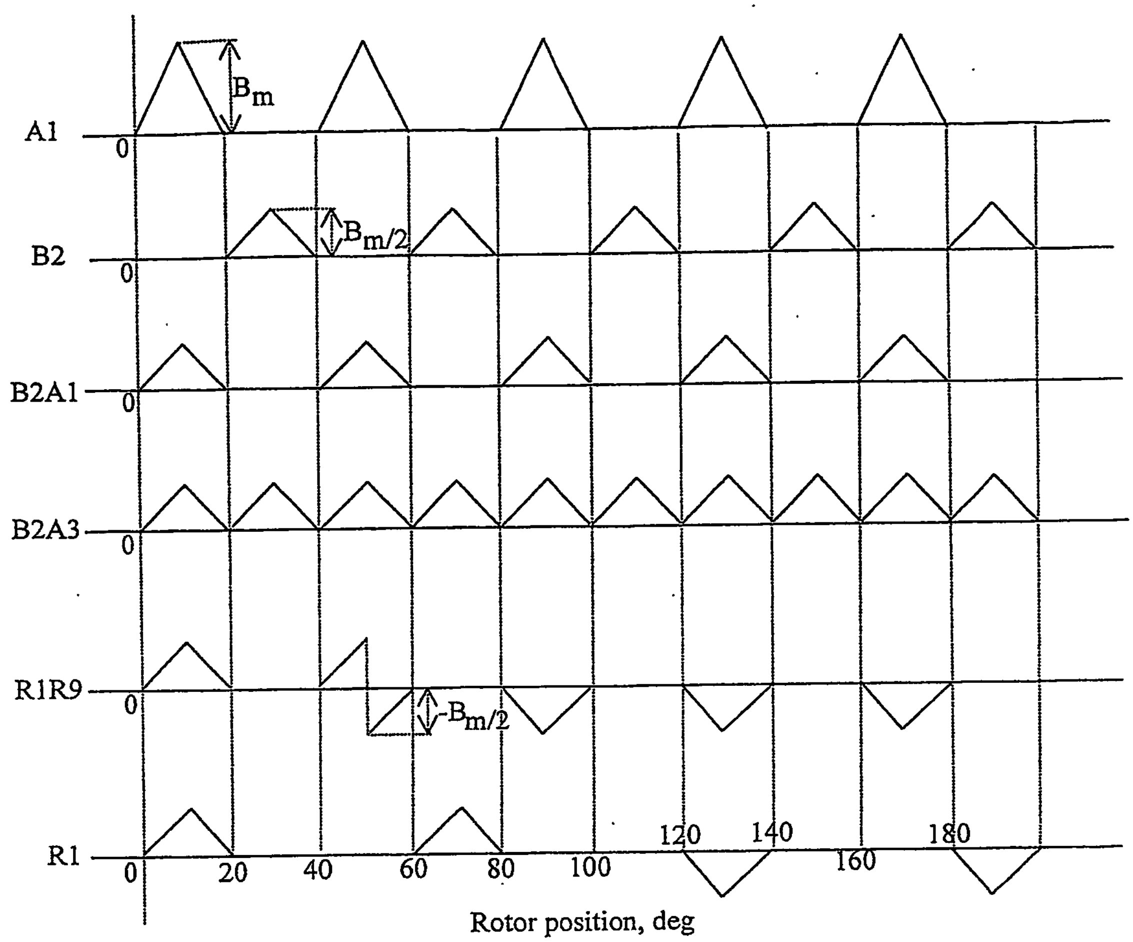

F_{B2R8}
F_{B3R2}
F_{B1R5}

FIG. 4B



A1
B2
B2A1
B2A3
R1R9
R1
Bm
Bm/2
-Bm/2
0
20
40
60
80
100
120
140
160
180
Rotor position, deg

FIG. 5

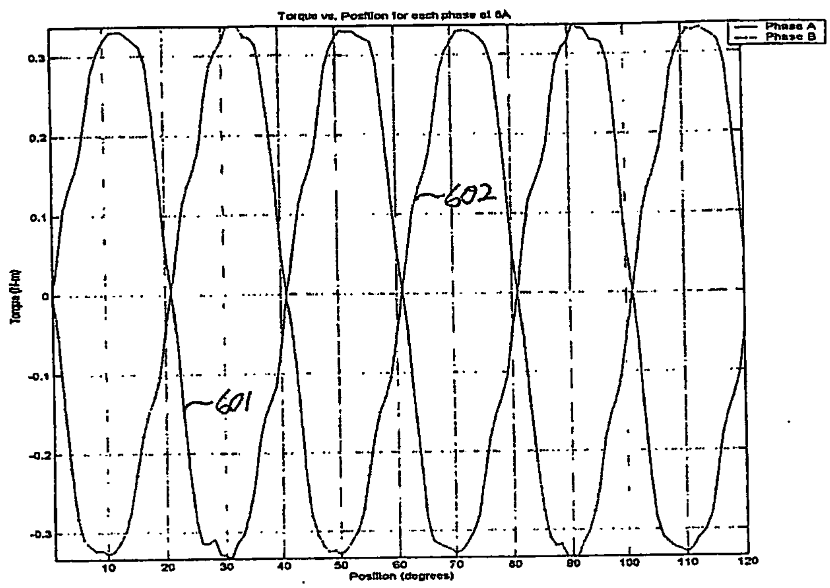

Torque vs. Position for each phase at 6A
Phase A
Phase B
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
10
20
30
40
50
60
70
80
90
100
110
120
Position (degrees)
~602
~601

FIG. 6

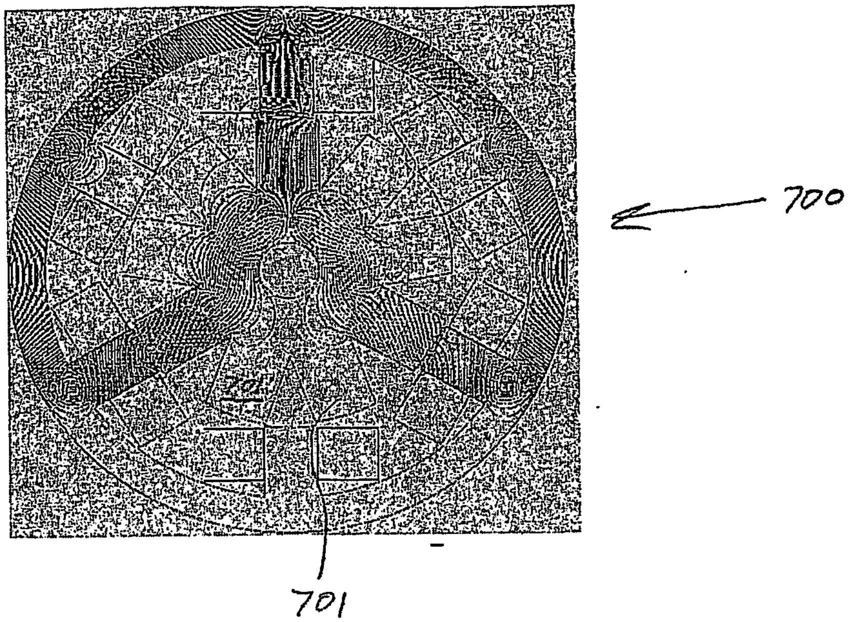
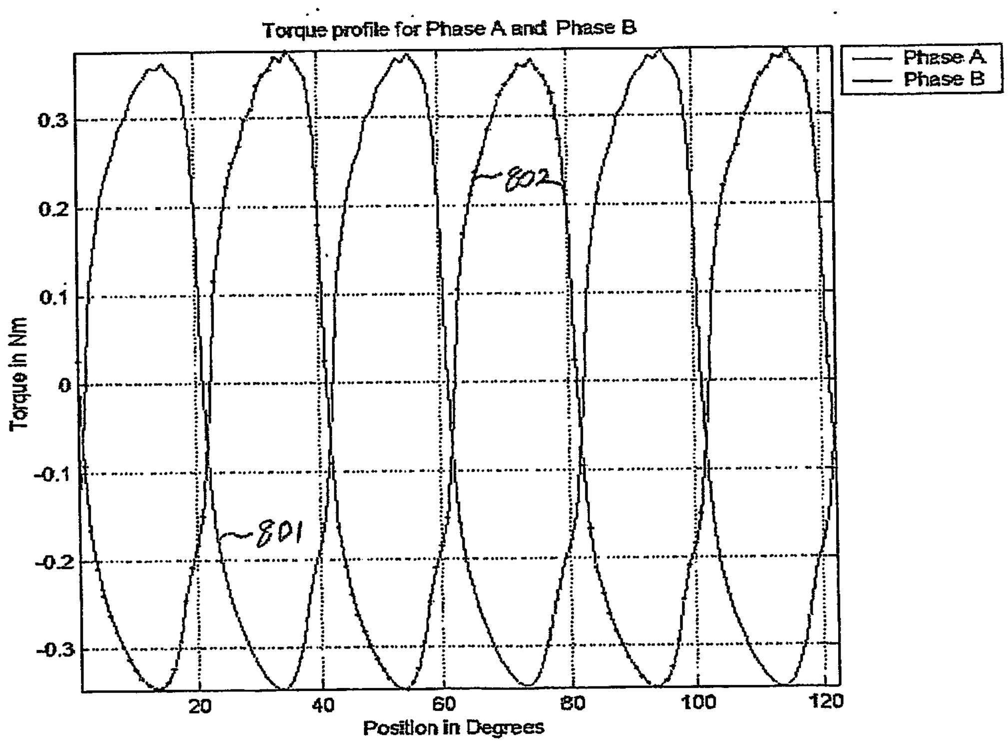


FIG. 7

FIG. 8


Torque profile for Phase A and Phase B
Phase A
Phase B
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
Torque in Nm
20
40
60
80
100
120
Position in Degrees
801
802

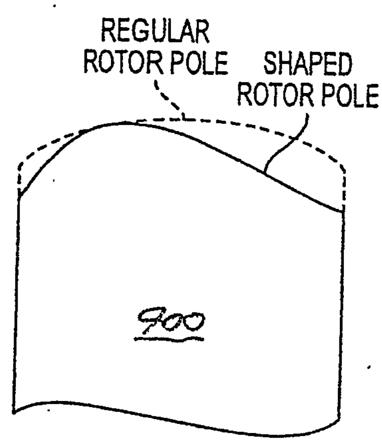


FIG. 9A

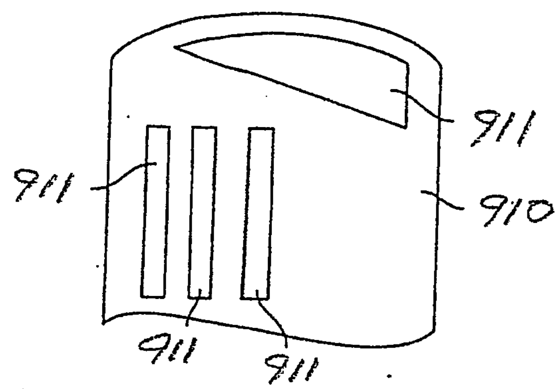


FIG. 9B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US04/08114

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) : H02K 19/00, 17/00, 17/42
US CL : 310/162, 166, 168
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 310/162, 166, 168

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6,051,903 A (PENGOV) 18 April 2000 (18.04.2000), see entire document.	1-20
X	US 6,194,805 B1 (HEESE et al) 27 February 2001 (27.02.2001), see entire document.	14
Y	US 5,146,127 A (SMITH) 08 September 1992 (08.09.1992), see entire document.	6, 7
Y	US 3,956,678 A (BYRNE et al) 11 May 1976 (11.05.1976), see entire document.	6, 7

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search
17 January 2005 (17.01.2005)

Date of mailing of the international search report
21 MAR 2005

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